Alberta Climate
Advisory Committee
Alberta Environment

SYMPOSIUM/WORKSHOP PROCEEDINGS

# THE IMPACT OF CLIMATE VARIABILITY AND CHANGE ON THE CANADIAN PRAIRIES

SEPTEMBER 9-11, 1987

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250 Karl Clark Road
Edmonton, Alberta

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Saskatchewan Climate
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Manitoba Climate
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# THE IMPACT OF CLIMATE VARIABILITY AND CHANGE ON THE CANADIAN PRAIRIES

Proceedings of the Symposium/Workshop

Edmonton, Alberta
1987 September 9-11

Edited by

B.L. MAGILL
F. GEDDES

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## FOREWORD

As chairperson of the Alberta Climate Advisory Committee (ACAC), it gives me great pleasure to introduce the Proceedings of the Symposium/Workshop on the Impact of Climate Variability and Change on the Canadian Prairies held in Edmonton, Alberta from 1987 September 9-11. This type of event was made possible only by the willing and full cooperation extended to ACAC by the Canadian Climate Centre, Saskatchewan Climate Advisory Committee, Manitoba Climate Advisory Committee, and the Climate Program Planning Board of Canada.

Adoption of recommendations from the Climate Change Seminar in 1981 sponsored by the Canadian Council of Resource and Environment Ministers stipulated the formation of a provincial advisory committee on climate. Organized in 1983, the objectives of the Alberta Climate Advisory Committee are threefold:

1. Identify the needs of the various climate data users in the Province and make recommendations concerning ways of meeting these needs;
2. Promote the accessibility and publication of Alberta climatic information and data; and
3. Identify the climatological concerns for Alberta which require research, monitoring, or other actions.

The Alberta Climate Advisory Committee has representatives from provincial and federal government departments, industry, and universities, as well as from the Alberta Climatological Association. Besides other planned and ongoing activities, the organization of a Symposium/Workshop to exchange scientific information among various groups was a key decision taken by ACAC in 1985 to fulfill its mandate. I sincerely hope that the workshop recommendations result in a joint federal/provincial action plan to understand and manage the issue of climate variability and change and its impact on the environment and economy of the Prairie Provinces.

I would like to express my deep appreciation to the co-sponsors of the Symposium/Workshop, members of the ACAC Steering Committee for effective organization, and the Alberta Research Council for hosting it. Special thanks are due to Honourable Ken Kowalski, Alberta's Minister of the Environment and Minister of Public Safety Services, for accepting the invitation to welcome the guests and for presenting the opening address on Climate and Its Impact on our Environment, Resources, and Economy.

September 1987

H.S. SANDHU
Chairperson, Alberta Climate
Advisory Committee
Alberta Environment

# PREFACE

There is a growing awareness of the potential economic, environmental, and social impacts of climate variability and change as illustrated by the following recent events in Western Canada. The summer drought of 1980 produced a record number of forest fires in Western Canada. Newspaper articles in the summer of 1987 highlighted the impact of hot, dry weather on grain crops in Western Canada and the potential for drought in Southern Alberta. Similarily, the recent tragic events resulting from tornadoes in central Alberta and the severe snow storms of the spring of 1986 and 1987 clearly demonstrate how the management and development of our resources are significantly affected by climate and climate variability. Natural events such as these including possible future droughts cannot be prevented. Short-term climate variability has and will continue to affect the resources and economy of the Canadian Prairies. In coming years, governments will have to develop and implement strategic plans to minimize the potentially adverse impacts and maximize the positive impacts of climate change and variability. It is important, therefore, to determine the relationship between climate and our resources and whether climate can be reliably predicted. To this end, many questions must be resolved and directions for research set.

This Symposium/Workshop was organized to consider the issue of climate variability and change and its impact on the Canadian Prairies. The Symposium provided a formal forum for the presentation and discussion of climate research activities relevant to the Canadian Prairies. The objectives of the Symposium were to:

1. Provide a perspective on and awareness of the causes and impacts of climate change and variability on the Canadian Prairies;
2. Exchange information on climate research; and
3. Enhance public and political awareness of the need for climate research.

The technical presentations covered a diverse range of topics from model simulation of global and regional climate change to descriptions of comprehensive impact assessment analyses and processes. Several impact studies related to the agriculture sector in the prairie provinces were presented with results linked to various climate change scenarios. The current state of climate research was discussed as was a proposed federal government drought response program. Papers on the impacts of climate variability on specific resource sectors such as forestry, energy, hydrology, and recreation completed the symposium session.

The Workshop provided the opportunity for intensive discussions of the issues arising from the Symposium. The objectives of the Workshop were to:

1. Identify issues and concerns related to climate variability and change; and
2. Identify and provide the rationale for future research and resource planning strategies for Western Canada.

Six concurrent workshops were held each dealing with a different, although to some degree interrelated topic:

1. Are the causes of climate variability and change known?
2. Planning for climate variability and change - who cares?
3. Is climate effectively used in our resource sectors?
4. Can we quantify the links between climate and our resources?
5. Is there sufficient communication regarding climate and its impacts?
6. What are the socio-economic impacts of climate variability and change?

These topics were used primarily to guide the discussions and pertinent issues and concerns related to climate change and variability on the prairies were identified. Recommedations were then formulated to address these issues and concerns. Through a general plenary session, the recommendations were priorized to provide clear direction for future thrusts in the area of climate change and variability on the Canadian Prairies.

The Symposium/Workshop was a major success. I would like to gratefully acknowledge the assistance and cooperation of the Steering Committee (Dr. Humphries, Mr. Hume, Mr. Malinauskas, and Dr. Singh) who contributed significantly to this successs.

**B.L. MAGILL**
Alberta Environment
Chairperson, Steering Committee
Climate Change Symposium/Workshop

## ACKNOWLEDGMENTS

The Steering Committee gratefully acknowledges the assistance of the many individuals who contributed to the success of the Symposium/Workshop. We especially thank the Honourable Ken Kowalski, Minister, Alberta Environment, and Minister, Alberta Public Safety Services, for giving the opening remarks and welcoming the participants. We also thank (1) Dr. F. Kenneth Hare, Dr. Michael Schlesinger, and Dr. Martin Parry for providing such interesting keynote addresses; and (2) the other speakers for sharing their research findings and thoughts with us. Our gratitude is also extended to the session chairpersons and workshop facilitators and recorders respectively for overseeing the sessions and ensuring that the workshops achieved their stated objectives.

A special note of thanks goes to Mr. Bob Grauman, Edmonton Social Planning Council, for assisting the Steering Committee in formulating the agenda for the workshops. We also express our appreciation to the Alberta Research Council for hosting the Symposium/Workshop and the various agencies who provided displays and poster sessions.

We also express our appreciation to the staff from Alberta Environment, the Alberta Research Council, and Environment Canada for their assistance in making the Symposium/Workshop a success. We especially thank Ms. Meliza Canafranca and Mr. Mike Brennand for assisting in the compilation of the Proceedings.

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# WELCOMING ADDRESS

## CLIMATE AND ITS IMPACT ON OUR ENVIRONMENT, RESOURCES, AND ECONOMY

by

THE HONOURABLE KEN KOWALSKI
Minister, Alberta Environment
Minister, Alberta Public Safety Services

Ladies and gentlemen, good morning and welcome to the Symposium and Workshop on the Impact of Climate Variability and Change on the Canadian Prairies. It's a great pleasure to be here today and I'm pleased to see that representatives from Saskatchewan, Manitoba, and Alberta, along with distinguished international speakers, can unite to share climate information on a unique region, the Canadian Prairies.

In 1983, industry, the academic community, the Alberta Research Council, and the Alberta Government Departments of Environment, Agriculture, and Forestry, Lands and Wildlife, at the request of the Canadian Council of Resource and Environment Ministers, assisted in forming the Alberta Climate Advisory Committee, of which the Alberta Climatological Association is a part. It is through the work of the Advisory Committee and its Steering Committee that this Symposium/Workshop is taking place and I commend these committees for their successful first time effort in hosting a symposium such as this one. Additionally, the support of the Canadian Climate Centre of Environment Canada and the Climate Advisory Committees of Saskatchewan and Manitoba signifies the importance of this topic.

From my perspective as Environment Minister and Minister Responsible for Public Safety Services, I am becoming increasingly aware of the importance of climate information. The recent tornado is a timely and very graphic example of how climate can affect us. While this natural disaster serves as one example of the negative impact of climate, I think it underscores the importance of how to prepare for such negative impacts and how to minimize them.

Conversely, it is equally important to maximize the positive impacts of climate. For example, the climate for growing coniferous timber in Alberta is conducive to producing some of the strongest lumber of its type on the continent. Consequently, Albertans can economically benefit by making use of Alberta's climatic conditions.

Alberta is a province that economically depends heavily on its natural resources. It is imperative that environmental and economic policies are in place to ensure that natural resources continue to be a source of prosperity for Albertans without exploiting them or the environment. The natural environment must be sustained in order to support productivity and quality of life for Albertans.

Rudimentary to environmental and resource economics is climate. It is a significant element in producing crops, trees, and water supply. Climate is a variable that helps to determine the degree of resource efficiency and productivity. A warm winter and a hot, dry summer in 1980 played havoc in Alberta and other western provinces. It resulted in a tremendous loss in the economy and a devastating forest fire situation, resulting in a severe loss of forest resources.

On the other side of the coin, snow storms in May 1986 and 1987 positively impacted our recreation industry through an extended alpine ski season. The snowfalls also helped to increase the water supply in southern Alberta, but contributed to the flood situation in northern Alberta. The snowfall also cost taxpayers extra money for snow removal and repairs to our utilities and communications sector. Clearly, climate variability and change has a very direct bearing on the economy.

Within the Alberta Government, Alberta Environment might be the most evident user of climate information. But, as I've just indicated to you, it also affects Departments such as Tourism, Agriculture, Economic Development, and Forestry, Lands and Wildlife. Obviously, I am most familiar with how Alberta Environment uses climate information. Within Alberta Environment, the most visible users of climate information are the River Forecast Centre and the Air Quality Control Branch. The River Forecast Centre uses climate data to forecast seasonal water supply, water availability, inflow to reservoirs, and short-term floods. These predictions help Albertans to plan and prepare for events such as the recent floods in north central Alberta and droughts in southern Alberta.

The Air Quality Control Branch uses climate data in computer models to describe and predict air quality which results from atmospheric emissions of pollutants. The transport and diffusion of pollutants in the atmosphere is controlled by the state of the atmosphere, making collection of meteorological data essential to air quality management. One of the most tangible applications of climate data includes stack design for industrial emissions.

The inaccurate location, height, or design of the stack can cost a company hundreds of thousands of dollars.

An associated concern to stack design and emissions is the long-range transport and deposition of pollutants. Of special concern is acidic deposition in the form of acid rain. At one time, scientists told us that by constructing taller stacks, the pollutants emitted from industrial plants would become more diffused, resulting in less local environmental deterioration.

This technology has resulted in a trade-off in eastern Canada. While the environment in the vicinity of the industrial processing plant has become less impacted, the long-range transport and deposition of stack emissions has led to environmental damage due to acid rain.

In Alberta, levels of acidic deposition are much lower than in eastern Canada. I'm very proud to mention that industrial sulphur dioxide emissions in Alberta have decreased approximately 15% from 1974 to 1983 as a result of Alberta Environment's air pollution control program. This occurred during a period when licensed industrial sources increased from 77 to 180.

It pleases me that the western provinces and the Federal Government have worked collectively in researching acid deposition and its effects. This was accomplished at the request of the Western and Northern Canada Long-Range Transport of Atmospheric Pollutants Technical Committee. This illustrates how we can work together on major issues which are transboundary in nature.

Similar initiatives related to climate have already been undertaken on an international scale. As part of the World Climate Impact Studies Program on the impacts of climatic variations on agriculture, the International Institute for Applied Systems Analysis and the United Nations Environment Program undertook a case study in Saskatchewan, which is representative of the Canadian Prairies. The study assessed the climatic impacts on food production in Saskatchewan.

The approach taken in both the Saskatchewan study and the acid deposition study can certainly be adapted for climate research in the prairie provinces. Alberta and the other Prairie Provinces must strive towards a unified and coordinated research program to understand climate variability and change and its impact on us. It is that same sense of purpose that brings us together to discuss issues related to climate.

Climate variability and change will continue to impact on the management and development of Alberta's and the prairie provinces' economic and human resources. Research is required to determine the interrelationships between climate and our resource/industrial sector. It is also needed to model and predict climate variability. This research will enable us to develop and implement strategic plans to minimize the potentially adverse impacts and maximize the positive impacts of climate variability and change.

To this end, many questions must be resolved and directions for monitoring and research must be established. Alberta Environment, in consultation with the Alberta Climate Advisory Committee, has initiated a major review of climate-related research and monitoring activities in the province. This, in addition to the Symposium papers and discussions, will help Alberta and the prairie provinces to formulate a sound and scientifically defensible research program for understanding climate and its impact on our environment, resources, and economy.

I heartily endorse the discussions and presentations being made over the next few days. I'm sure you can all look forward to an illuminating Symposium and Workshop. Once again, welcome to the Symposium and Workshop on the Impact of Climate Variability and Change on the Canadian Prairies.

## OPENING ADDRESS

# VULNERABILITY TO CLIMATE

by

F. KENNETH HARE
Chairman
Climate Programme Planning Board of Canada

My title is a little different from the programme version. I've changed my tune since I sent in my abstract. All the real experts are on the programme anyway, and I want neither to scoop them nor to expose my ignorance. Instead I shall claim an elder's privilege and talk about the broader significance of what we have come here to discuss.

"Vulnerability" is the key word. What system, what processes, what domains are capable of being so stressed by climate that they may suffer serious damage? Does the list include human society? Specifically, does it include the Prairie economy?

These questions were posed, and partially answered, here in Alberta only two weeks ago at The Civilization and Rapid Climate Change Conference organized by the Institute of the Humanities at the University of Calgary, and brilliantly led by Harold Coward, the Institute's Director. It opened up new perspectives for me. Growing originally out of the nuclear winter debate (Starley Thompson and George Golitzyn were there), the Conference's scope grew to cover the entire question of the impact of catastrophic events on civilization. In the group were leading archaeologists, anthropologists, biologists, and geographers. As a team, we put together the beginnings of a consistent position.

Here in Edmonton, we shall be looking at things from a different perspective. We shall consider processes that are much slower than the effect of an asteroid impact, or of nuclear war. Yet they are overwhelmingly faster than the great majority of non-catastrophic, geological, or evolutionary changes. Climate varies on all accessible time-scales, but the ones of interest here are slower than the true catastrophes of geological history. We are fond of saying that the lower atmosphere is inertial, meaning that to alter its fundamental behaviour one has to move a lot of mass about; and that the ocean has, in addition, high thermal inertia, meaning that to alter its properties one has to redistribute an enormous amount of heat. Both ideas propel our thinking toward rather slow changes.

We have become used to the idea that climatic variation has two components. These are:

1. Slow shifts, over decades or centuries, in the distribution of mass and heat within the ocean and atmosphere. This reveals a gradual global change of temperature in both media. The Greenhouse Effect works on this time scale. We think of these slower shifts as being climatic changes. If they reverse themselves in a few decades we call them fluctuations. The Greenhouse Effect involves predicted temperature changes of the order $10^{-1}$K/a, which is much slower than, for example, this morning's rise in temperature in Edmonton, which was of the order 1 K/h. Accompanying the changes in temperature are necessary changes of pressure distribution, of oceanic and atmospheric circulation, and of precipitation.
2. More rapid, but obviously non-permanent, shifts between years or decades in mean temperature and circulation in the atmosphere and ocean. This climatic variability appears to be an inherent property of the present climate (and probably of all previous climates). It arises from the internal properties of the climate itself, and is hence an integral part of that climate. Anomalous years or decades, such as the 1930s in the Great Plains and Prairies, are reflections of such variability. Popular recollections of such events colour our judgement about their importance. They are more extreme than the slower shifts we call climatic change, and they end with a return to something more normal, though that word defies exact definition. Some climates sustain up to three decades of such anomalies before the system returns to something more like its modal long-term state.

This distinction, which is not wholly valid, but is useful in practice, means that the climatic record is full of sound and fury, which dominate shorter-term records. Thus the dry 1930s in the Prairies were succeeded by the wetter 1940s. Behind these noisy fluctuations, one may be able to detect the faint signal of longer-term climatic change. Temperature time-series, even when smoothed, sometimes make such a resolution possible.

The Greenhouse Effect, if it is to be detected, will appear as a faint signal or trend behind the heavy noise of short-term fluctuations. These fluctuations are always larger than the long-term trend. As everyone knows, this plays havoc with public perception. People are ready to believe that a warm winter like 1986-87 is the Greenhouse Effect showing up. They have a lot more trouble sustaining that belief through a cold winter. A single year's rain in the Sahel makes politicians forget about drought.

It is usually asserted that climatic change on the scale of a century to many millennia is caused by changes in external factors: variations in the solar constant, build up of absorbers or scatterers in the atmosphere, and so on. We assume, by contrast, that the shorter-term fluctuations arise from internal processes, such as exchanges of heat between atmosphere and ocean, perhaps involving very large-scale quasi-periodic processes analogous to the El Nino Southern Oscillation (ENSO) phenomenon, or the quasi-biennial mode seen in so many climatic records. There is little to justify such beliefs, other than hunch; but one must start somewhere if one is to model climate successfully.

The papers by Mike Schlesinger and George Boer, outstanding modellers both, will put a quantitative cast-of-countenance on these ideas. In leaving the subject, may I remark that the word "climate" has changed its meaning greatly in my lifetime. We used to think of it as the powerful invariant that lay behind the meaningless froth called weather. Now we realize that what we call climate is the best description we can give to the modes of variation in time and space, in the ocean and atmosphere, that are characteristic of our planet. What a change!

To return to vulnerability: how robust are the systems impacted by climate? This Symposium will hear from a number of outstanding authorities who can answer that question better than I can. I am impressed by the explosion of new results now coming forward. Stewart Cohen's work on the Great Lakes, for example, has achieved wide circulation. So have Martin Parry's results; in particular, the studies by the team who worked with him at IIASA. I have the individual reports of the latter, and am still waiting for the book. The succeeding papers on Wednesday get down to details as regards western agriculture. On the Prairies, farming is practiced near to both the cold and dry margins. Both margins will figure in these discussions. Finally, we shall look at terrestrial ecosystems and the forests, related questions that are hot topics in the Prairie Provinces, since some Greenhouse projections extend grassland-climates (or what we often assume are such) down to the Mackenzie delta.

Several analyses of the question of climatic impact have appeared in the literature. Usually, they predict that a small decrease in either temperature or rainfall will imperil prairie agriculture. What is now foreseen by the modellers is a rise in temperature, but (in some models) a decrease in available soil moisture during the growing season for spring-sown crops (due mainly to increased evaporation, rather than a loss of rainfall). I am eager to see how our speakers treat these countervailing influences. I hope that the Symposium will give adequate weight to a homely principle: that what can be done now can still be done in the future, if necessary somewhere else. I am unimpressed when farmers are said to face ruin from changes that will give them a climate like that of eastern Nebraska.

I plead, in other words, that we develop not only mechanistic models of crop-climate linkages, but economic models that take adequate account of technological change and the remarkable adaptability of farmers. Having been born on a large wheat farm, I have great respect for the farmer's capacity to adapt. Farming's deadliest current enemy is not climate, not accumulating pesticides, not soil impoverishment; instead it is ruinously low prices engineered by absurd economic practices, chiefly in the European Economic Community. Until pricing sanity returns to the world, if it ever does, farmers and governments alike will be unable to take a long-term view of the subjects we are discussing. They will be too scared of bankruptcy.

Does this mean that we all go home? Clearly not. This Symposium has broader, long-term objectives. We are apt to forget, while we analyze our crop-climate models, that agriculture, forestry, and fisheries all depend on world-scale commodity exchanges and price effects. Global demand for food presses upward at about three percent per annum and it does not take long for such an exponential to eat into a surplus of grain. The long-term prospect for agriculture, including pastoralism, is good. I doubt whether biotechnological development will really supersede field photosynthesis as a way of converting solar energy, at least for quite a while. Whether the market is for edible grains, meat, or usable wood, I expect our capacity to produce these in great quantities will again become profitable, as it has already done in the forest industries. You would never guess, from a reading of the literature on agricultural economics, that climate is a major control of such profitability along the geographic margin, and is also a major selector of suitable technologies; but indeed I think it is.

My own view is that western agriculture is more robust in the presence of climatic stress than we usually give it credit for. But it is far from immune from pressures, especially drought. We came here to examine them. It is my hunch that the forests may be more vulnerable, through the effect of fire and disease. We shall leave Edmonton with some answers.

It is all otherwise in Africa, and perhaps in monsoon Asia and northeast Brazil, where the experience of the past four decades has been intense and traumatic. Africa especially has seen the birth and virtual death of hope: hope for independence and the right to build new nations; hope for an end to hunger and warfare; hope for stable, responsible government. Almost none of these things have been realized. Northeast Brazil defies the best efforts of the federal government. Frequent droughts undermine the local economy, and fertility rates remain high. In Asia, drought has returned to India, which has recently achieved food self-sufficiency. If drought persists, or becomes frequent, the advances will soon be reversed. I have long felt that southeast Asia was uniquely vulnerable to drought, which it has mercifully escaped in prolonged form in recent decades.

Why do these things matter to Canadians? An honourable reply is that no one can be indifferent to suffering. On humanitarian grounds alone Canadians must respond, as they showed so spectacularly at the climax of the starvation in Ethiopia. But there is another reason for concern. Our farm exports and prices depend heavily on the pattern of overseas demand. To be a bit gruesome, other peoples' misfortunes may be our opportunity. Further, our very large foreign aid programme (administered in part by the Canadian International Development Agency [CIDA], part by International Development and Relief Commission [IDRC], and part by voluntary groups) is much influenced by climatic fluctuations.

Beyond this vast domain is an even more diffuse but crucial subject. It is conceivable that climatic stress may stimulate nation-building (in all its complexities). We no longer quote Toynbee at length; still less Semple and Huntingdon. But there remains the question: how does climatic stress affect the intangibles of the world order? Is it possible to disentangle climatic impact from the host of other influences? This is far more than a problem in the analysis of variance. It involves a host of dimly-perceived social and political forces that I for one am quite unqualified to discuss. To be specific, can anyone in this room answer the question: just how has Canada's harsh and unpredictable climate influenced our evolution as a nation? Various historians have tried to answer this question, but always in a qualitative fashion that fails to convince. Perhaps there is no hard answer.

At the recent Calgary Conference on Civilization and Rapid Climate Change, I was exposed to an excellent array of anthropologists, geographers, archaeologists, and historians who appeared more optimistic. But they were talking of natural disasters and their consequences. They felt that, for these sudden events, one could identify a sequence of stages that repeated themselves for a wide variety of disasters and over a wide range of cultures. Famine was the case described because the discussion focussed on the survivors of a nuclear war. The nuclear winter was very much on the agenda. I was author of the Conference overview and I now paraphrase its outcome.

To begin with, as hunger spreads, there is a phase of common effort as people realize the danger confronting them. Then, as famine deepens, they begin to draw in among themselves to protect their families; they eat behind drawn curtains. Finally, as they realize that no solution is in hand, they reach a condition of apathy. As they do so, institutions and corporations wither and society disintegrates. Homes are abandoned and an aimless drift towards any conceivable relief begins. If this rot goes too far, it becomes irreversible. Only a new culture can replace the old. Bryson spoke of the decline of the Harappan civilization in these terms, and there are other examples. It was generally agreed that whatever might survive a nuclear winter would owe little to the pre-war situation. Anthony Verrier, the British political commentator, drew our attention to an obvious exception: the recovery of the Netherlands after the starvation of 1944 to 1945. This was a culture that retained more of its discipline and cohesion through oppression and famine that, in some cities, killed four-tenths of the citizenry. Most of those present in Calgary felt that this could not be achieved in the broader context of entire continents, which lack the cohesiveness of a proud nation.

What we are considering at this Symposium is something altogether more subtle, but actually more probable, since I'm optimistic enough to believe that all-out nuclear war will be avoided and that natural disasters will remain extremely rare in Canada. One of the myths that recent events, and Mike Newark's research, have discredited is that tornadoes stop at the US/Canada border. Damaging tornado storms do indeed occur even as far north and west as Edmonton. But the betting is strong that the climatic evolution we are discussing will unfold without punctuation by catastrophe. There is ample time, in my view, to adapt to the Greenhouse Effect, though perhaps not to the related ozone-layer effect.

Ample time to adapt! These are not words to appeal to the media or to environmental activists. But I am sure they are valid. Once we are finally persuaded of the reality of the Greenhouse Effect, as I already am, our role will be to guide and influence that adaptation. We may also have to persuade governments to postpone the effect by cutting back on fossil fuel use, by encouraging energy conservation and the use of non-carbonaceous fuels, and by putting a lid on population growth. I will lay a bet now (my head on the table) that governments will be reluctant to cut back, and will prefer that we adapt. So we had better be ready with plans to meet the challenge.

I am going to be reckless and suggest a number of ways in which this challenge might be risen to:

1. I think the time has come when long-term capital investment, whether public or private, should take precautionary account of probable forthcoming changes in snowcover, run-off, rainfall,

evaporation, and length of freeze-up and thaw. All decisions regarding arctic and inland navigational facilities, hydroelectric power development, and irrigation works should do likewise. I think also that the choice of modes of power development (e.g., coal versus nuclear) should take note of possible calls for cut-backs on fossil fuel use.

2. The agricultural scientist, hydrologist, and forester should develop strategies to deal with a gradual change in mean temperature, run-off and soil moisture, and the calendar dates on when things happen. When it shows up, the Greenhouse Effect will appear, like many recent years on the prairie provinces, as an altered incidence of warm, dry years.
3. Governments should ensure that monitoring of the impending changes is adequately tackled, and that the right kinds of research and development go forward.
4. Our combined professions (for this is a widely interdisciplinary, inter-professional concern) should be alert to the significance of what is happening and advise governments and industry in good time on what is about to, or has, come about.

My own preference is that we avoid wild statements and predictions of disaster. I agree that the Greenhouse Effect is likely to alter quite drastically the environmental equilibrium to which our economy is adapted. But it will do so on a time-scale to which the international markets and exchange systems can adapt. Economic change can be traumatic, but it can also be effective in challenging ingenuity. I have lived through several economic convulsions: the great depression, World War II, and the huge expansion of the fifties to the seventies. I have watched world population double, and go some way towards a further doubling. Somehow, a system of world order, of economic growth, and a rise in living standards has emerged from these traumas. I do not believe that they could survive nuclear war; but I have no doubt that human ingenuity can adapt, if it has to, to the probable consequences of the Greenhouse Effect. It would be better avoided; but if we can't avoid it, we can still cope with it.

Symposia such as this are a necessary part of the preparations we must make. I congratulate Dr. Sandhu for the initiative. He has long been one of the Canadian Climate Programme Planning Board's most enthusiastic and discerning members. Alberta has been heard from a good deal over the past few years. I hope that the discussions are fruitful, and appreciate having been given the chance to start them off.

# PART I: TECHNICAL PAPERS

## SESSION I

## CLIMATE MODELLING

CHAIRPERSON: George Boer
Climate Modelling Division
Canadian Climate Centre

## KEYNOTE ADDRESS

# MODEL PROJECTIONS OF THE EQUILIBRIUM AND TRANSIENT CLIMATIC CHANGES INDUCED BY INCREASED ATMOSPHERIC $CO_2$

by

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## ABSTRACT

Simulations of $CO_2$-induced equilibrium climatic change by energy-balance, radiative-convective, and general circulation models are reviewed and characterized in terms of the direct radiative forcing of the increased $CO_2$, the response of the climate system in the absence of feedback processes, and the feedbacks of the climate system.

The direct radiative forcing due to a doubling of the $CO_2$ concentration is about 4 $Wm^{-2}$ for the surface-troposphere system. In the absence of feedbacks, the gain (output/input) of the climate system is about 0.3°C/($Wm^{-2}$), and the change in the surface air temperature is therefore about 1.2°C. Surface energy-balance models (SEBMs) have given a warming induced by a $CO_2$ doubling of about 0.2 to 10°C. This wide range is the result of the inherent difficulty in specifying the behaviour of the atmosphere in SEBMs. Radiative-convective models (RCMs) have given a warming of about 0.5 to 4.2°C for a $CO_2$ doubling. This range is the result of water vapour, lapse rate, surface albedo, cloud altitude, cloud cover, and cloud optical depth feedbacks. General circulation models (GCMs) have given a warming of about 1.3 to 5.2°C for a $CO_2$ doubling. This also is a result of the feedbacks listed above, except for those due to cloud optical depth feedback, which has not yet been included in the GCM simulations of $CO_2$-induced climatic change.

Five recent simulations of $CO_2$-induced climatic change by atmospheric GCM/mixed-layer ocean models are contrasted in terms of their surface air temperature and soil moisture changes. These comparisons reveal qualitative similarities but quantitative differences.

The simulations of $CO_2$-induced transient climatic change by planetary energy-balance, radiative-convective, and general circulation models are reviewed in terms of the e-folding time $_e$ of the response of the climate system. Simplified models have given an e-folding time of about 10 to 100 years for the response of the climate system to an abrupt increase in the $CO_2$ concentration. A simulation with a global coupled atmosphere/ocean

general circulation model indicated that $\tau_e$ is about 50 to 100 years as a result of the transport of the $CO_2$-induced surface heating into the interior of the ocean. Theoretical studies for a time-dependent $CO_2$ increase between 1850 and 1980 indicate that this sequestering of heat into the ocean's interior is responsible for the concomitant warming being only about half that which would have occurred in the absence of the ocean. These studies also indicate that the climate system will continue to warm toward its as-yet unrealized equilibrium temperature change, even if there is no further increase in the $CO_2$ concentration.

## ACKNOWLEDGMENTS

I would like to thank Syukuro Manabe and Richard Wetherald of the Geophysical Fluid Dynamics Laboratory; James Hansen, Gary Russell, Andrew Lacis and David Rind of the Goddard Institute for Space Studies; Warren Washington and Gerald Meehl of the National Center for Atmospheric Research; and John Mitchell of the United Kingdom Meteorological Office for making their results available to me. I express my gratitude to Dean Vickers for performing some of the calculations herein, and to John Stark, Larry Holcomb, and Linda Haygarth for drafting. This study was supported by the National Science Foundation and the U.S. Department of Energy under grant ATM 87-12033.

## 1. INTRODUCTION

If the Earth's atmosphere were composed of only its two major constituents, nitrogen ($N_2$, 78% by volume) and oxygen ($O_2$, 21%), the Earth's surface temperature would be close to the -18°C radiative-equilibrium value necessary to balance the approximately 240 $Wm^{-2}$ of solar radiation absorbed by the Earth-atmosphere system. The fact that the Earth's global-mean surface temperature is a life-supporting 15°C is a consequence of the Greenhouse Effect of the atmosphere's minor constituents, mainly water vapour ($H_2O$, 0.2%) and carbon dioxide ($CO_2$, 0.03%). Measurements taken at Mauna Loa, Hawaii show that the $CO_2$ concentration has increased from about 315 ppmv in 1958 to 346 ppmv in 1985 (Keeling and Boden 1986), a 10% increase in 28 years. Measurements of the air entrapped within the ice sheet of Antarctica indicate that the pre-industrial $CO_2$ concentration increased from about 280 ppmv in 1750 to 290 ppmv in 1880 (Siegenthaler and Oeschger 1987). Rotty and Masters (1985) report that, with the exception of the periods of the Depression and World Wars I and II, the $CO_2$ concentration increased from 1860 to 1949 due to a 4.2% $yr^{-1}$ growth in the consumption of fossil fuels (gas, oil, coal). Subsequently, the growth rate of $CO_2$ emissions was a steady 4.4% $yr^{-1}$ from 1950 to 1973, and then decreased to 1.5% $yr^{-1}$ from 1973 to 1982 as a result of the rise in the price of oil. A probabilistic scenario analysis of the future usage of fossil fuels predicts about an 80% chance that the $CO_2$ concentration will reach twice the pre-industrial value by 2100 (Nordhaus and Yohe 1983). Computer simulations of the equilibrium climatic change induced by a doubling of the $CO_2$ concentration have been made with a hierarchy of mathematical climate models, the most recent of which has given a warming as large as 5.2°C in the global-mean surface air temperature. Since such a global warming trend is comparable to that which is estimated to have occurred during the transition from the last ice age to the present interglacial (Gates 1976a, b; Imbrie and Imbrie 1979), there is considerable interest in the detection of a $CO_2$-induced climatic change, and in the potential impacts of such a change on the spectrum of human endeavours.

The majority of the simulations of $CO_2$-induced climatic change have been performed to determine the change in the equilibrium climate of the

Earth resulting from an abrupt increase in $CO_2$ such as a doubling from 300 to 600 ppmv. The goal of these simulations has been to estimate the magnitude of the eventual climatic change which may occur as a consequence of the doubled $CO_2$ concentration projected to occur in the next century. These equilibrium climatic change simulations have not been concerned with the time required for the climatic change to reach its equilibrium and, in fact, have generally tried to minimize that time in an effort to economize on computer time. More recently, concern has been focussed on the detection of a $CO_2$-induced climatic change. A simple scaling of the equilibrium 2 x $CO_2$-induced warming to the increase in $CO_2$ from 1861 to 1984 indicates an increase in the global-mean surface temperature of about 1.0°C; this for a sensitivity of 4°C for a $CO_2$ doubling. However, the observed surface temperature increase over this period is only about half this value (Jones et al. 1986). This discrepancy suggests that either the equilibrium warming of our climate models is twice as large as that of nature, or that there is a lag in the response of the climate system. The latter possibility has been the focus of research on the transient response of climate to both abrupt and time-dependent increases in the $CO_2$ concentration. In the following, the studies of equilibrium and transient climatic change induced by increased $CO_2$ are reviewed in Sections 2 and 3, respectively; a summary of these results is presented in Section 4, and conclusions are given in Section 5.

## 2. $CO_2$-INDUCED EQUILIBRIUM CLIMATIC CHANGE

Three different types of climate model have been used to simulate the change in the equilibrium climate resulting from an increase in the $CO_2$ concentration: (1) energy-balance models (EBMs), (2) radiative-convective models (RCMs), and (3) general circulation models(GCMs). These models and their projections of $CO_2$-induced climatic change are described below.

### 2.1 ENERGY-BALANCE MODELS

Energy balance models predict the change in temperature at the Earth's surface, $\Delta T_s$, from the requirements that $\Delta N = 0$, where N is the net energy flux expressed by $N = N(E, T_s, I)$. Here E is a vector of quantities that can be regarded as "external" to the climate system; that is, quantities whose change can lead to a change in climate, but which are independent of climate. I is a vector of quantities that are internal to the climate system; that is, quantities that can change as the climate changes and, in so doing, feed back to modify the climatic change. The external quantities include, for example, the solar constant, the optically- active ejecta from volcanic eruptions, and, for the present purpose, the $CO_2$ concentration (although eventually it may change as a result of climatic change). The internal quantities include all variables of the climate system other than $T_s$. Since $T_s$ is the only dependent variable in an EBM, the internal quantities must be represented therein by functions of $T_s$; that is, by $I = I\ (T_s)$.

A small change in the energy flux, $\Delta N$, can be expressed as

$$\Delta N = \Delta Q - (G_o^{-1} - F)\,\Delta T_s$$

where

$$\Delta Q = \sum_i \frac{\partial N}{\partial E_i}\,\Delta E_i$$

is the change in N due to a change in one or more external quantities, $\Delta E_i$,

$$-G_o^{-1}\,\Delta T_s = \frac{\partial N}{\partial T_s}\,\Delta T_s$$

is the change in N due to the change in $T_s$ alone, and

$$F\,\Delta T_s = \sum_j \frac{\partial N}{\partial I_j}\,\frac{dI_j}{dT_s}\,\Delta T_s$$

is the change in N due to the change in the internal variables I through their dependence on $T_s$. When the equilibrium $\Delta T_s$ is reached in response to the forcing $\Delta Q$, $\Delta N = 0$ and

$$\Delta T_s = \frac{G_o}{1 - G_oF} \Delta Q = \frac{G_o}{1 - f} \Delta Q = G_f \Delta Q \; . \qquad (1)$$

This relation can be represented by a feedback block diagram for the climate system as shown in Figure 1. It is seen that $G_0$ is the gain (output/input) of the climate system when the feedback $f = G_0F = 0$. Thus, $G_0$ is the zero-feedback gain and $(\Delta T_s)_0 = G_0\Delta Q$ is the zero-feedback temperature change; correspondingly, $G_f$ and $\Delta T_s$ are the gain and the temperature change with feedback. Letting

$$R_f = \Delta T_s/(\Delta T_s)_0 = G_f/G_0,$$

it can be seen from Figure 2 that $0 < R_f < 1$ when the feedback is negative ($f < 0$), and $R_f > 1$ when the feedback is positive ( $0 < f < 1$). Consequently, the sign of the response is always the same as the sign of the forcing, even when there is a negative feedback, regardless of its magnitude. This is in contrast to what has sometimes been erroneously inferred for the outcome of negative feedback (e.g., Nature 1987). On the other hand, for the positive feedback, $f > 1$, $R_f < 0$, and the sign of the response is opposite to that of the forcing. This outcome, while mathematically possible (and actually obtained by one improperly formulated EBM; see Schlesinger 1985, 1988a), is not physically-consistent and must therefore be rejected.

Energy-balance models impose the condition $\Delta N = 0$ at either the Earth's surface or the top of the atmosphere. The former models may be called surface energy-balance models (SEBMs), and the latter, planetaryenergy-balance models (PEBMs). SEBMs have given a warming induced by a $CO_2$ doubling of about 0.2 to 10°C. This wide range is due in part to the inherent difficulty in specifying the behaviour of the atmosphere in terms of the surface temperature in SEBMs; that is, $I(T_s)$, and to the large sensitivity of $\Delta T_s$ in SEBMs to this specification (Schlesinger 1985, 1988a). Therefore, it is preferable to use models which calculate the atmosphere's behaviour based on the fundamental laws of physics.

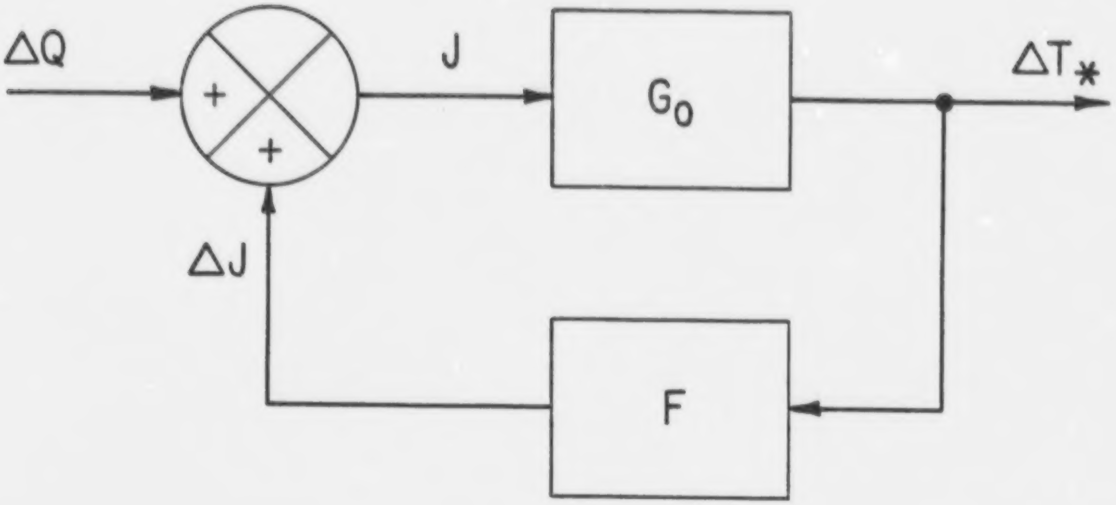
ΔQ
+
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Figure 1. Block diagram of the climate system with a feedback loop. (From Schlesinger 1985).

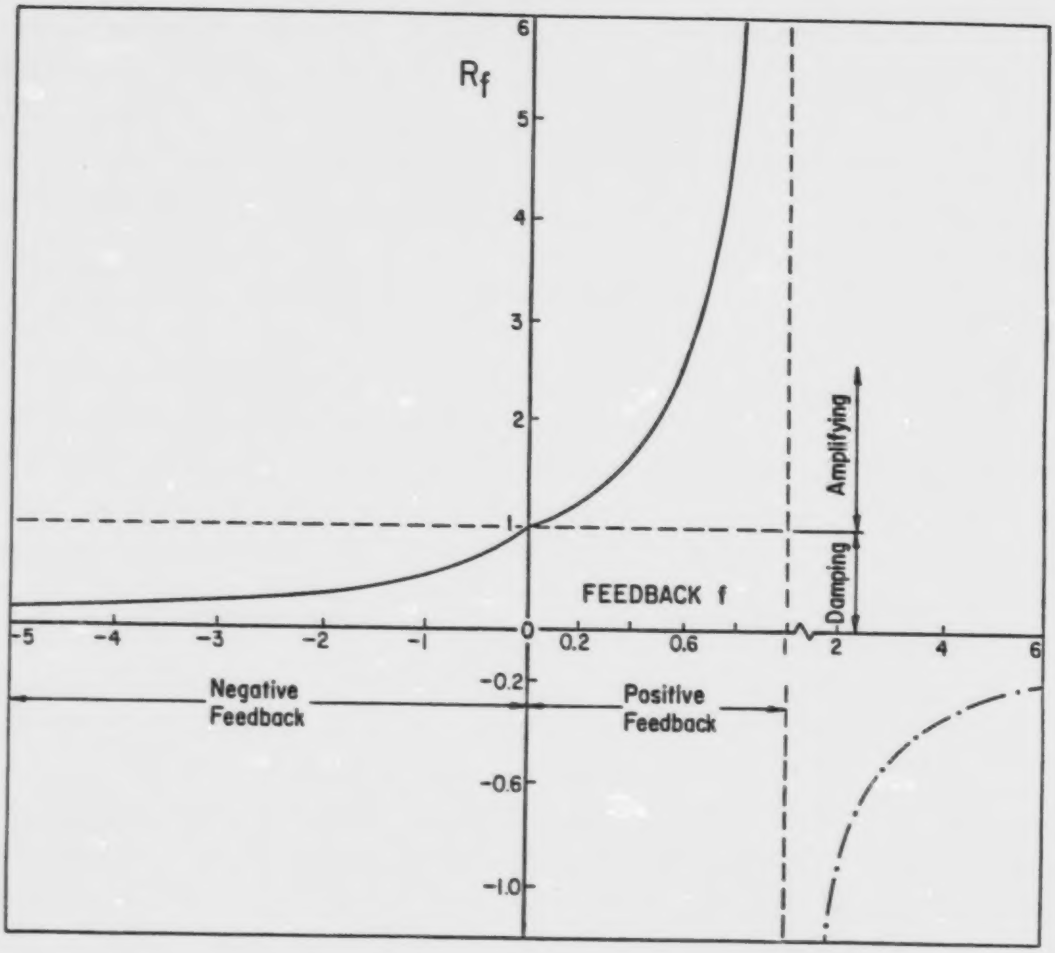

Figure 2. The ratio of the surface temperature change $\Delta T_s$ to the zero-feedback value $(\Delta T_s)_0$, $R_f = \Delta T_s/(\Delta T_s)_0$, versus the feedback f. (From Schlesinger 1985).

Before turning our attention to these physically-based models, it is useful to consider PEBMs for which

$$N = \frac{1 - \alpha_p}{4} S - \varepsilon\sigma T_s^4 ,$$

where S is the solar constant, $\alpha_p$ the planetary albedo, $\varepsilon$ the effective emissivity of the Earth-atmosphere system, and $\sigma$ the Stefan-Boltzmann constant. From this equation, we can estimate the zero-feedback gain as

$$G_o = -\left(\frac{\partial N}{\partial T_s}\right)^{-1} = \frac{T_s}{(1 - \alpha_p) S} , \qquad (2)$$

an expression which we will use subsequently. For a PEBM, $\Delta T_s$ is given by Equation (1) with Equation (2) and

$$f = G_o \sum_j \frac{\partial N}{\partial I_j} \frac{dI_j}{dT_s} ,$$

where $I_j$ are again the internal variables of the climate system. This expression means that the feedback depends on the specification of the behaviour of the atmosphere and the Earth's surface. Thus, PEBMs also have the same problem as SEBMs; namely, the need to treat the behaviour of the climate system away from the energy-balance level. In PEBMs, this has been done semi-empirically following the initial studies by Budyko (1969) and Sellers (1969). The equilibrium surface temperature change for a $CO_2$ doubling given by PEBMs ranges from 0.6°C (Rasool and Schneider 1971) to 3.3°C (Ramanathan et al. 1979).

## 2.2 RADIATIVE-CONVECTIVE MODELS

Radiative-convective models (RCMs) determine the equilibrium vertical temperature distribution for an atmospheric column and its underlying surface, for given solar insolation, prescribed atmospheric composition, and surface albedo. An RCM includes submodels for the transfer of solar and terrestrial (longwave) radiation, the turbulent heat transfer between the Earth's surface and atmosphere, the vertical redistribution of heat within the atmosphere by dry or moist convection, and the atmospheric water vapour content and clouds. The radiative transfer models used in RCMs are frequently identical to those used in GCMs. The surface heat exchange is treated either as an equivalent radiative exchange or is parameterized as a Newtonian exchange with a prescribed transfer coefficient. The vertical heat redistribution by convective atmospheric motions is modelled as an adjustment, whereby the temperature lapse rate of the atmosphere is prevented from exceeding some given value. The amount of water vapour is determined by RCMs either by prescribing the absolute humidity or the relative humidity; in the latter case, the amount of water vapour increases (decreases) with increasing (decreasing) temperature. Finally, the fractional cloudiness and the altitude of the clouds are either prescribed or predicted, the latter by some assumption about the behaviour of clouds.

The equilibrium change in temperature, simulated by RCMs for an increase in the $CO_2$ concentration, shows a cooling in the stratosphere and a warming in the troposphere and at the Earth's surface; the latter with a range of 0.48 to 4.2°C. As indicated by Equation (1), the change in the surface temperature induced by a doubling of the $CO_2$ concentration can be understood in terms of the direct radiative forcing $\Delta Q$ due to the $CO_2$ increase; the response of the climate system if the surface temperature alone changed, as characterized by the zero-feedback gain, $G_0$; and the negative and positive feedbacks, f, which occur to reduce and enhance the zero-feedback response, respectively. Each of these is discussed below.

About 95% of the direct radiative forcing due to the increase in the $CO_2$ concentration occurs in the longwave radiation emitted by the Earth and 5% in the shortwave solar radiation (Ramanathan et al. 1979). The direct radiative forcing of the troposphere-surface system $\Delta R_T$ has been found to be 4.0 $Wm^{-2}$, of which 2.7 $Wm^{-2}$ is contributed by the reduction in upward flux from the troposphere, 1.55 $Wm^{-2}$ by the increased downward flux from the stratospheric $CO_2$ increase, and -0.15 $Wm^{-2}$ by the decreased solar flux at the tropopause (Lal and Ramanathan 1984).

The response of the climate system to the direct radiative forcing of the increased $CO_2$, when only the surface temperature is allowed to change, is given by Equation (1), with $f = 0$ and $\Delta Q = \Delta R_T$, and by Equation (2) as

$$(\Delta T_s)_o = G_o \, \Delta R_T = \frac{T_s(1xCO_2)}{(1 - \alpha_p)S} \, \Delta R_T \, .$$

Taking $S = 1370 \ Wm^{-2}$, $\alpha_p = 0.3$, and $T_s$ as the observed surface air temperature, $T_a = 288$ K gives $G_o = 0.3^oC/(Wm^{-2})$. Thus for $\Delta R_T = 4 \ m^{-2}$, $(\Delta T_s)_o = 1.2 \ ^oC$. This value of $(\Delta T_s)_o$ is in agreement with what has been obtained by RCMs without feedbacks (see Schlesinger 1985, 1988a).

The feedback f of the $CO_2$-induced surface air temperature warming given by RCMs can be determined from Equation (1) written as

$$f = 1 - \frac{(\Delta T_s)_o}{\Delta T_s} \, , \qquad (3)$$

together with the above estimate of $(\Delta T_s)_o$. Thus, for the $0.48 \leq T_s \leq 4.2^oC$ range simulated by RCMs, $-1.5 \leq f \leq 0.7$. Several physical mechanisms are thought to be the cause of this wide range in the feedback of these models. For increasing $T_s$, these mechanisms include:

1. The increase in the amount of water vapour in the atmosphere as a consequence of the near-constancy of the relative humidity;
2. The change in the temperature lapse rate;
3. The increase in the cloud altitude as the clouds maintain their temperature;
4. The change in cloud amount;
5. The change in the cloud optical depth; and
6. The decrease in surface albedo.

The feedbacks of these physical processes, as determined by applying Equation (3) to an ensemble of RCM simulations, in which the feedbacks were added sequentially (see Schlesinger 1985, 1988a), are summarized in Table 1. This table shows that:

Table 1. Summary of the feedbacks f in RDM and GCM simulations of $CO_2$-induced surface air temperature change.

| Feedback Mechanism | RCM[a] | GCM | |
|---|---|---|---|
| | | GISS[b] | GFDL[c] |
| Water Vapour | 0.3 to 0.4 | 0.66 | 0.41 |
| Lapse Rate[d] | | | |
| BADJ | 0.1 | | |
| MALR | -0.25 to -0.4 | | |
| PC | -0.65 | | |
| Total | | -0.26 | 0.05 |
| Cloud | | | |
| Altitude | 0.15 to 0.30 | | |
| Cover | Unknown | | |
| Altitude & Cover | | 0.22 | 0.09 |
| Optical Depth | 0 to -1.32 | | |
| Surface Albedo | 0.14 to 0.19 | 0.09 | 0.13 |
| Total | -1.5 to 0.71 | 0.71 | 0.68 |

[a] Based on analysis of Schlesinger (1985, 1988a).

[b] Based on the results of Hansen et al. (1984).

[c] In this analysis, a value of $\Delta R_T = 4.3\ Wm^{-2}$ is assumed. This value is based on the change in the net radiation at the top of the atmosphere given by Wetherald and Manabe (1988), $\Delta R_0 = 2.28\ Wm^{-2}$, and the difference between the $\Delta R_T$ and $\Delta R_0$ results for this radiation model averaged over the five atmospheric profiles of the Intercomparison of Radiation Codes used in Climate Models (ICRCCM) study (Ellis, 1987, personal communication).

[d] BADJ, MALR, and PC denote baroclinic adjustment, moist adiabatic adjustment, and penetrative convection, respectively.

1. The water vapour, cloud altitude, and surface albedo feedbacks are positive, with values that decrease in that order;
2. The cloud optical depth feedback is negative;
3. The temperature lapse rate feedback is either positive or negative, depending on whether the lapse rate is controlled by baroclinic adjustment (BADJ) or convective (MALR or PC) processes; and
4. The cloud cover feedback is unknown.

However, as shown by Equation (1) and Figure 2, the influence of any of these feedbacks on the response of the climate system depends nonlinearly on the sum of the other feedbacks. For example, the addition of cloud altitude feedback with $f = 0.2$ would increase $\Delta T_s$ by 1.6°C if added to a system with an existing feedback of 0.5, but would increase $\Delta T_s$ by only 0.5°C if added to a system with no existing feedback.

## 2.3 GENERAL CIRCULATION MODELS

While EBMs and RCMs calculate only the surface temperature and the vertical temperature profile, respectively, General Circulation Models (GCMs) calculate the geographical distributions of an ensemble of climatic quantities, which includes the: (1) vertical profiles of atmospheric temperature, water vapour, and velocity and, (2) the surface pressure, precipitation, soil water, and snow. In addition, GCMs used for climatic change simulations must calculate the geographical distributions of the sea surface temperature (SST) and sea ice extent. (See Schlesinger 1984 and 1988b for further information on GCMs). To study $CO_2$-induced equilibrium climatic changes with a GCM requires two simulations: a 1 x $CO_2$ simulation with a $CO_2$ concentration generally taken to be 300 to 330 ppmv, and an N x $CO_2$ simulation with N generally taken to be 2 or 4. Each of the simulations is begun from some prescribed initial conditions and is run until these conditions are forgotten and the simulated climate reaches its statistically stationary equilibrium state. The differences between the N x $CO_2$ and 1 x $CO_2$ equilibrium climates are then taken to be the $CO_2$-induced equilibrium climatic changes.

The earliest GCM simulations of $CO_2$-induced climatic change were performed with so-called "swamp-models" of the ocean. In such a swamp ocean model, the ocean has zero heat capacity and no horizontal or vertical heat transports. Therefore, the swamp ocean is like perpetually wet land and is always in thermodynamic equilibrium. Consequently, the time for the Earth-atmosphere system to reach its equilibrium climate with an atmospheric GCM/swamp ocean model depends only on the atmosphere and land surface, and generally requires about 300 days. While such models are economical of computer time, they must be run without the seasonal insolation cycle to prevent the freezing of the ocean in the latitudes of the polar night. Consequently, these models simulate the $CO_2$-induced change only for a surrogate of the annual-mean climate; namely, that which is obtained for the annual-mean solar insolation. More recently, atmospheric GCMs have been coupled to prescribed-depth, mixed-layer ocean models which have heat capacity and sometimes a prescribed additional oceanic heating, which includes the effects of oceanic heat transport. These atmospheric GCM/prescribed-depth, mixed-layer ocean models are run with the seasonal insolation cycle and generally require about 20 simulated years to reach their equilibrium climate. An additional 10 years is generally simulated to obtain estimates of the means and other statistics of the equilibrium climate.

The annual cycles of the equilibrium climatic changes induced by a doubling of the $CO_2$ concentration have been simulated by the GCM/mixed-layer ocean models of:

1. The Geophysical Fluid Dynamics Laboratory (GFDL, Wetherald and Manabe 1986);
2. The Goddard Institute for Space Studies (GISS, Hansen et al. 1984);
3. The National Center for Atmospheric Research (NCAR, Washington and Meehl 1984);
4. Oregon State University (OSU, Schlesinger and Zhao 1988); and
5. The United Kingdom Meteorological Office (UKMO, Wilson and Mitchell 1987).

In the following two subsections, the $CO_2$-induced changes in the surface temperature and soil water simulated by these models are presented.

### 2.3.1 Surface Air Temperature Change

The equilibrium changes in the global-mean surface air temperature $\Delta T_s$ simulated by the five models for a doubled $CO_2$ concentration are presented in Table 2, together with the global-mean precipitation changes $\Delta P$. This table shows that the simulated $CO_2$-induced changes in the annual-mean, global-mean surface air temperature range from 2.8 to 5.2°C, and the corresponding changes in precipitation from 7.1 to 15% of their 1 x $CO_2$ values. Furthermore, this table shows that the size of $\Delta P$ is positively correlated with the size of $\Delta T_s$, this occurring as a result of the Clausius-Clapeyron relation between the saturation vapour pressure of water vapour and temperature.

A partial explanation for the range of $\Delta T_s$, and thus of $\Delta P$, is provided by Figure 3 which displays the $CO_2$-induced warming versus the annual-mean, global-mean surface air temperature of the simulated 1 x $CO_2$ climate. This figure shows that the warmer the 1 x $CO_2$ control climate, the smaller the $CO_2$-induced warming. This is due in part to the decrease in the positive ice-albedo feedback with increasing 1 x $CO_2$ temperature, as a result of there being less sea ice and snow. From this, it appears that the $CO_2$-induced changes in temperature and precipitation simulated by these models would be in better agreement if their 1 x $CO_2$ global-mean surface air temperatures were in better agreement. Furthermore, it is tempting to conclude that the resulting common model temperature and precipitation sensitivities would be correct if the common 1 x $CO_2$ surface air temperature were in better agreement with the observed temperature, perhaps through the use of the "Flux Correction Method."[1]

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[1] In this method, which was employed by the GISS and UKMO models, an oceanic heating is determined for each calendar month at each ocean grid point from a 1 x $CO_2$ simulation with the atmospheric GCM, using the observed annual cycle of SST as its lower boundary condition over the ocean. This heating field is then prescribed in both the 1 x $CO_2$ and 2 x $CO_2$ simulations with the GCM/mixed-layer ocean model, thereby helping the model to reproduce the observed SST distribution in the 1 x $CO_2$ simulation. However, although the prescribed oceanic heating includes the effects of the oceanic heat transports, it also includes a compensation for the air/sea heat flux errors of the atmospheric GCM in its simulation with the observed SSTs. Therefore, this "Flux Correction Method" is not a physically-based method. Furthermore, its use in both the 1 x $CO_2$ and 2 x $CO_2$ simulations does not allow the oceanic heat transport effects to change and contribute to the $CO_2$-induced climatic change.

Table 2. Changes in the global-mean surface air temperature ($T_s$) and precipitation rate (P) simulated by atmospheric GCM/mixed-layer ocean models for a $CO_2$ doubling.

| Model/Study | $\Delta T_s$ (°C) | $\Delta P$ (% of 1 x $CO_2$ value) |
|---|---|---|
| GFDL/Wetherald & Manabe (1986) | 4.0 | 8.7 |
| GISS/Hansen et al. (1984) | 4.2 | 11.0 |
| NCAR/Washington & Meehl (1984) | 3.5 | 7.1 |
| OSU/Shlesinger & Zhao (1988) | 2.8 | 7.8 |
| UKMO/Wilson & Mitchell (1987) | 5.2 | 15.0 |

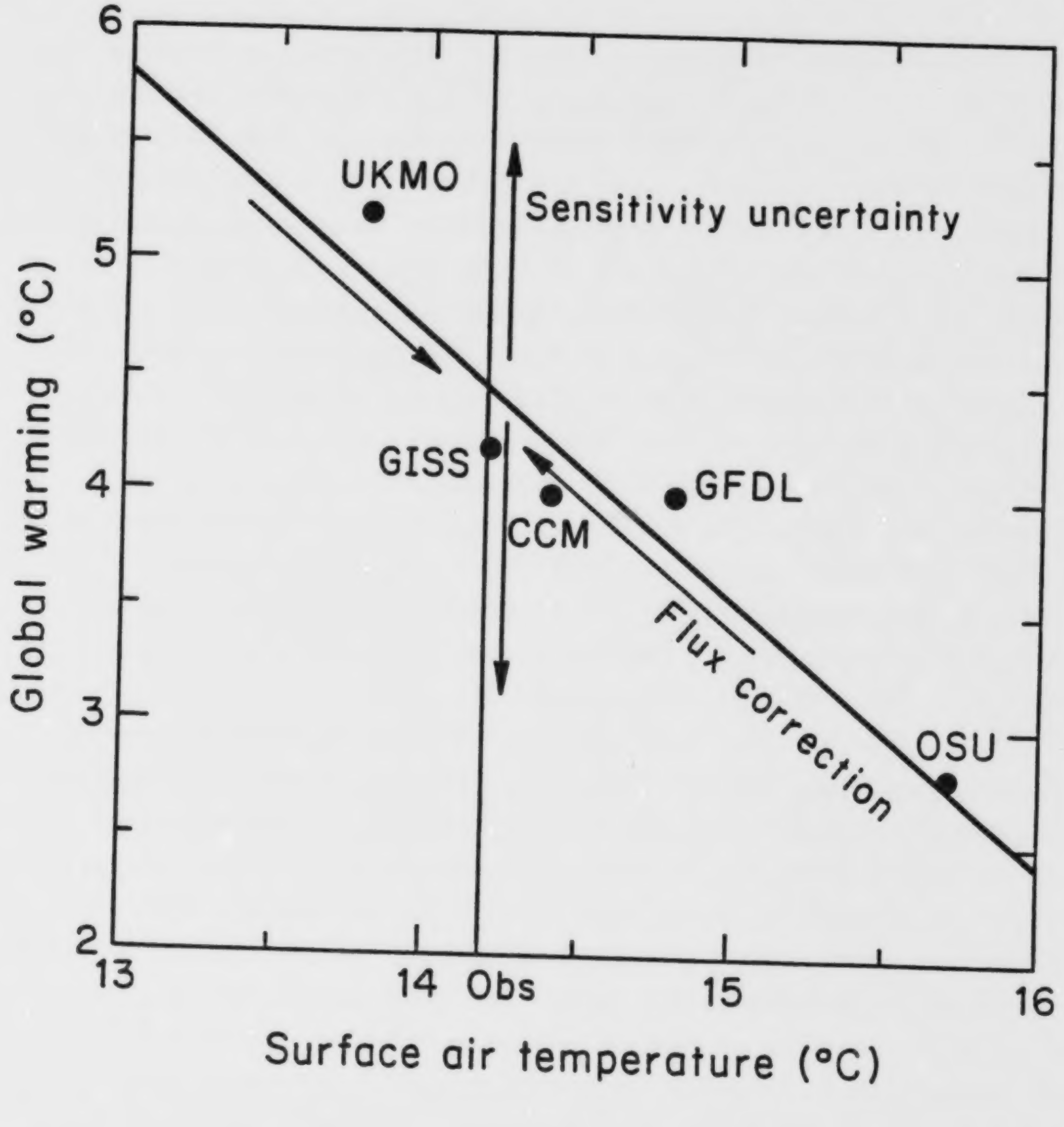

Figure 3. The global-mean surface air temperature warming simulated for a $CO_2$ doubling by five GCMs [the GDFL model (Wetherald and Manabe 1986), the GISS model (Hansen et al. 1984), the NCAR model (Washington and Meehl 1984), the OSU model (Schlesinger and Zhao 1988), and the UKMO model (Wilson and Mitchell 1987)] versus their simulated 1 x $CO_2$ global-mean surface air temperature. "Obs" indicates the observed global-mean surface air temperature based on the data of Jenne (1975). (Adapted from Cess and Potter 1988).

However, while this is a necessary condition for the common sensitivities of the models to be in agreement with the sensitivities of nature, it is not a sufficient condition, as is indicated by the vertical arrows labelled sensitivity uncertainty in Figure 3. In fact, the potential for such a disparity is evidenced by Table 1 which shows that, although the GISS and GFDL models simulate similar values of $T_s$ (Figure 3), they do so with feedbacks that differ in both magnitude and sign, despite the approximate agreement of their simulated values of $T_s$ for the 1 x $CO_2$ climate. Consequently, to establish the correctness of the models' temperature and precipitation sensitivities, when they simulate the present climate correctly, requires the simulation of at least one climate different from that of the present (e.g., that of the Wisconsin Ice Age 18 000 years before the present) and the comparison of such a simulated paleoclimate with observations. This requirement for model validation is a fundamental and inherently difficult problem in climate modelling and simulation (Schlesinger and Mitchell 1985, 1987). Notwithstanding this, it is of interest here to present and compare further results of the $CO_2$-induced climatic changes simulated by these models.

The time-latitude distributions of the zonal-mean surface air temperature changes simulated by the five models for doubled $CO_2$ are presented in Figure 4. This figure shows that the $CO_2$-induced temperature changes increase from the tropics (where the values range from about 2°C for the NCAR and OSU models to about 4°C for the GISS and UKMO models) toward the poles. It also shows that the seasonal variations of the $CO_2$-induced surface temperature changes are small between 50°S and 30°N, and are large in the regions poleward of 50° latitude in both hemispheres. In the Northern Hemisphere, a warming minimum of about 2°C is simulated near the pole by all five models in summer. The models also simulate a warming maximum in fall with values that range from 8°C for the NCAR model to 16°C for the GDFL and UKMO models. This maximum extends into winter in all the simulations except that of NCAR, which instead exhibits a warming minimum near the pole. The NCAR model also simulates another polar warming minimum in spring that is not found in the other

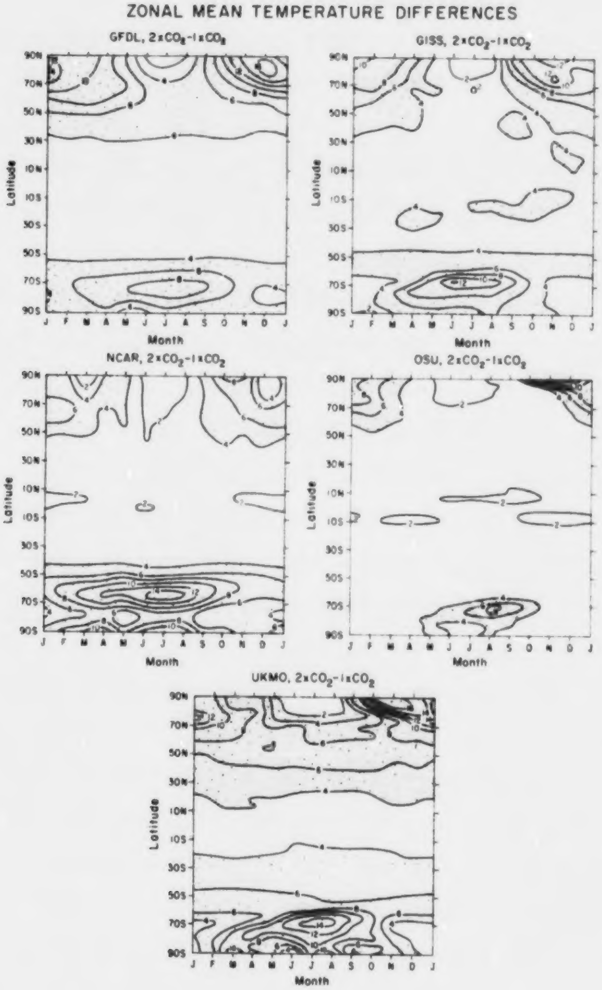

Figure 4. Time-latitude distribution of the zonal-mean surface air temperature change (°C), 2 x $CO_2$ - 1 x $CO_2$, simulated by: (a) the GDFL model by Wetherald and Manabe (1986); (b) the GISS model by Hansen et al. (1984); (c) the NCAR model by Washington and Meehl (1984); (d) the OSU model by Schlesinger and Zhoa (1988); and (e) the UKMO model by Wilson and Mitchell (1987). Stipple indicates temperature increases larger that 4°C.

simulations. In the Southern Hemisphere, all five models simulate a maximum warming in winter and a minimum warming in summer. The summer warming maximum occurs near the Antarctic coast in all five simulations and ranges from 8°C in the GDFL and OSU simulations to 14°C in the NCAR and UKMO simulations.

The geographical distributions of the 2 x $CO_2$ - 1 x $CO_2$ surface temperature changes, simulated for December-January-February (DJF) and June-July-August (JJA) by the five models, are presented in Figures 5 and 6, respectively. These figures show that all five models simulate a $CO_2$-induced surface air temperature warming virtually everywhere. In general, the warming is a minimum in the tropics during both seasons, at least over the ocean, and increases toward the winter pole. The tropical maritime warming minimum ranges from about 2°C in the NCAR and OSU simulations to about 4°C in the GFDL, GISS, and UKMO simulations. Maximum warming in DJF occurs in the Arctic in all the simulations except that of NCAR, which instead exhibits a warming maximum near 65°N. The maximum warming in JJA occurs around the Antarctic coast in all five simulations. The locations of the wintertime warming maxima in both hemispheres coincide with the locations where the 1 x $CO_2$ sea ice extent retreats in the 2 x $CO_2$ simulation. The magnitude of the wintertime warming maxima in the Northern Hemisphere ranges from 10°C in the GISS and OSU simulations to 20°C in the UKMO simulation, and in the Southern Hemisphere it ranges from 10°C in the OSU simulation to 20°C in the UKMO simulation. In JJA, there is a warming minimum in the Arctic of about 2°C in all five simulations.

Figures 5 and 6 also show that, although there are similarities in the $CO_2$-induced regional temperature changes simulated by the models, there are significant differences in both their magnitude and seasonality. For example, in North America the wintertime warming generally increases with latitude in the GDFL, GISS, and UKMO simulations with values of 4°C in the south and 10°C in the north, while both the NCAR and OSU simulations exhibit a warming minimum of 2°C centred over Canada and over the Pacific Northwest, respectively. Also, the $CO_2$-induced warming in summer, compared to that in winter, is simulated to be smaller by the GISS and

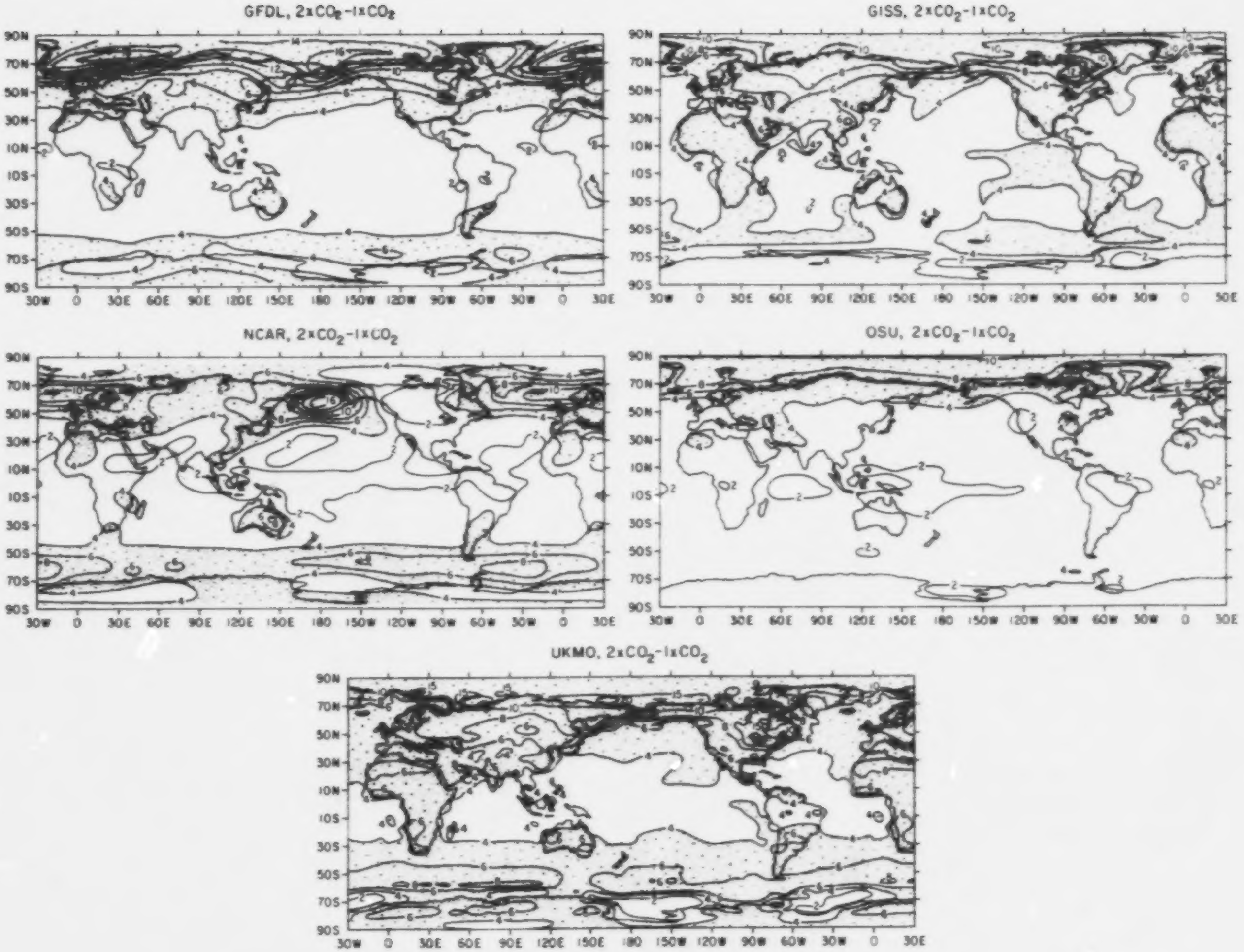
GFDL, $2 \times CO_2 - 1 \times CO_2$
GISS, $2 \times CO_2 - 1 \times CO_2$
NCAR, $2 \times CO_2 - 1 \times CO_2$
OSU, $2 \times CO_2 - 1 \times CO_2$
UKMO, $2 \times CO_2 - 1 \times CO_2$
90N
70N
50N
30N
10N
10S
30S
50S
70S
90S
30W
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
30E

Figure 5. Geographical distribution of the surface air temperature change ($^{0}$C), 2 x $CO_2$ - 1 x $CO_2$, for DJF simulated by: (a) the GDFL model by Wetherald and Manabe (1986); (b) the GISS model by Hansen et al. (1984); (c) the NCAR model by Washington and Meehl (1984); (d) the OSU model by Schlesinger and Zhao (1988); and (e) the UKMO model by Wilson and Mitchell (1987). Stipple indicates temperature increases larger than 4$^{0}$C.

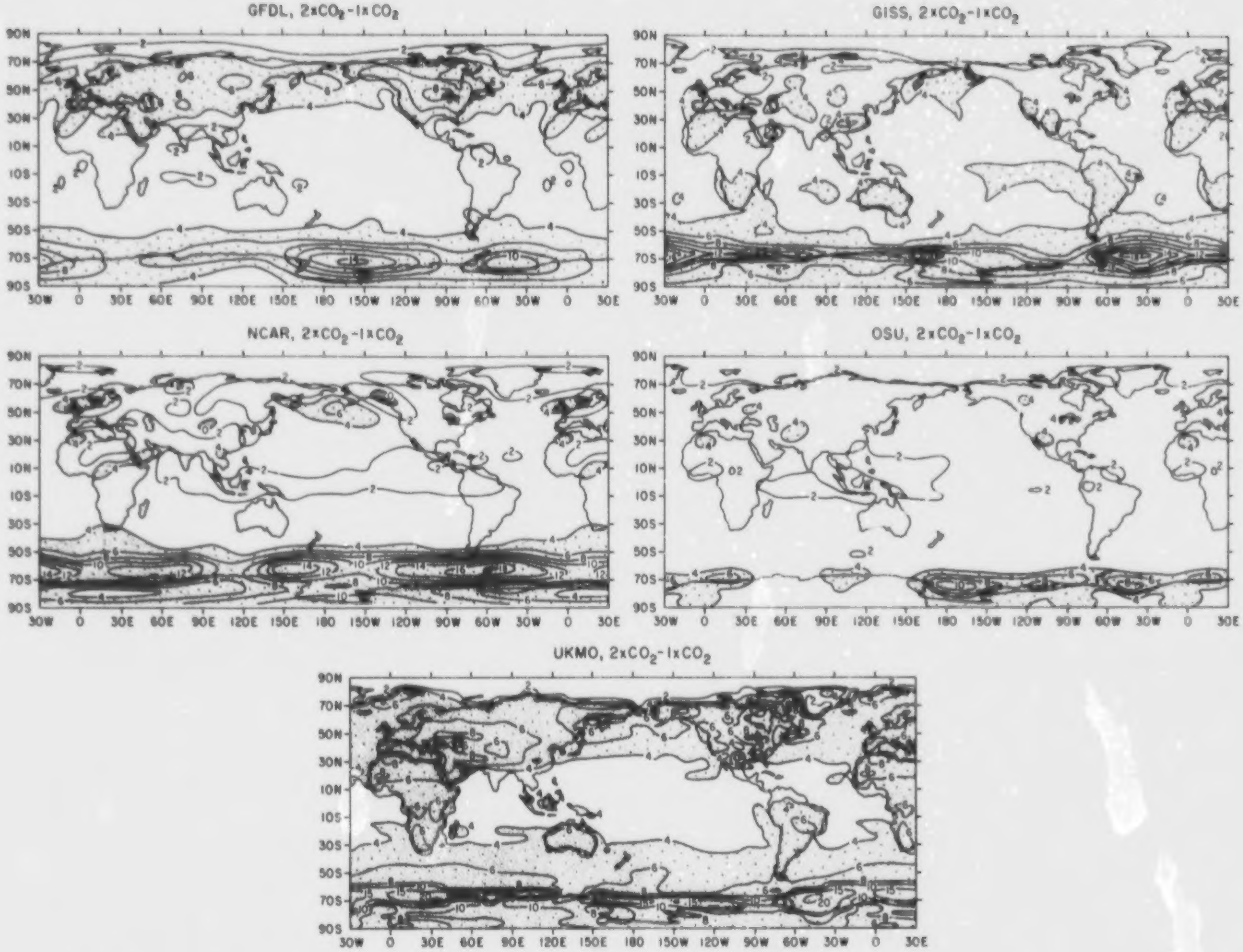
GFDL, 2xCO2-1xCO2
GISS, 2xCO2-1xCO2
NCAR, 2xCO2-1xCO2
OSU, 2xCO2-1xCO2
UKMO, 2xCO2-1xCO2
90N 70N 50N 30N 10N 10S 30S 50S 70S 90S
30W 0 30E 60E 90E 120E 150E 180 150W 120W 90W 60W 30W 0 30E

Figure 6. Geographical distribution of the surface air temperature change ($^{o}$C), 2 x $CO_2$ - 1 x $CO_2$, for JJA simulated by: (a) the GDFL model by Wetherald and Manabe (1986); (b) the GISS model by Hansen et al. (1984); (c) the NCAR model by Washington and Meehl (1984); (d) the OSU model by Schlesinger and Zhao (1988); and (e) the UKMO model by Wilson and Mitchell (1987). Stipple indicates temperature increases larger than 4$^{o}$C.

NCAR models, to be comparable by the GFGD, OSU and UKMO models, and to be larger by the NCAR model. Further similarities and differences can be seen for the $CO_2$-induced temperature changes simulated for the other continents.

### 2.3.2 Soil Water Change

The time-latitude distributions of the zonal-mean soil water change over ice-free land simulated by the five models for doubled $CO_2$ are presented in Figure 7. This figure shows that all five models simulate an increased soil water during winter in the Northern Hemisphere from about $45^oN$ to $70^oN$. In the Northern Hemisphere summer, the GISS and NCAR models simulate a minimum increase in soil water, while the GFDL, OSU, and UKMO models simulate a decreased soil water from about $30^oN$ to $70^oN$.

The geographical distributions of the $CO_2$-changes in soil water over ice-free land simulated by the models for the DJF and JJA are presented in Figures 8 and 9, respectively. As was evidenced by the zonal-mean soil water changes shown in Figure 7, all five models simulate a moistening of the soil over much of Eurasia and North America in DJF. On the other hand, the GISS and NCAR models simulate both regions of increased and decreased soil water over Eurasia and North America in JJA, while the GFDL, OSU, and UKMO models simulate a desiccation virtually everywhere in the Northern Hemisphere during summer. A similar desiccation of the Northern Hemisphere soil was first obtained in the "annual-mean" simulations with atmospheric GCM/swamp ocean models and in the first annual-cycle simulation with an atmospheric GCM/prescribed-depth, mixed-layer ocean model (See Schlesinger and Mitchell 1985, 1987).

## 3. $CO_2$-INDUCED TRANSIENT CLIMATIC CHANGE

As discussed in the Introduction, the $CO_2$ concentration has increased from about 288 ppmv in 1861 to 344 ppmv in 1984 (Siegenthaler and Oeschger 1987; Keeling and Boden 1986). The equilibrium surface temperature increase corresponding to this $CO_2$ increase can be written by Equation (1) as

$$\Delta T_s = G_f \Delta Q ,$$

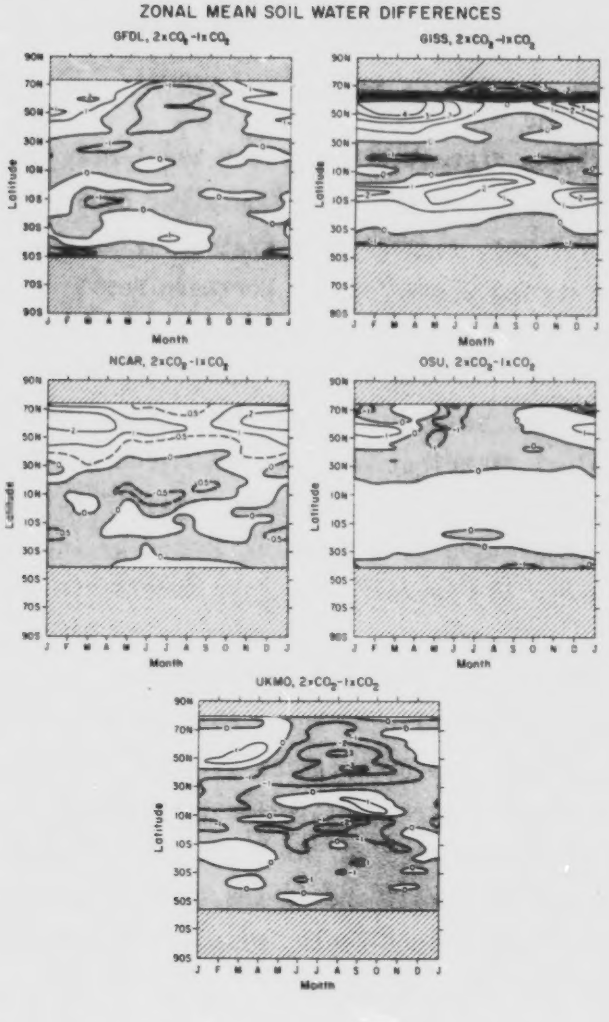

Figure 7. Time-latitude distribution of the zonal-mean soil water change (cm), 2 x $CO_2$ - 1 x $CO_2$, only over ice-free land simulated by: (a) the GDFL model by Wetherald and Manabe (1986); (b) the GISS model by Hansen et al. (1984); (c) the NCAR model by Washington and Meehl (1984); (d) the OSU model by Schlesinger and Zhao (1988); and (e) the UKMO model by Wilson and Mitchell (1987). Stipple indicates a decrease in soil water, hatching indicates latitudes where there is no ice-free land.

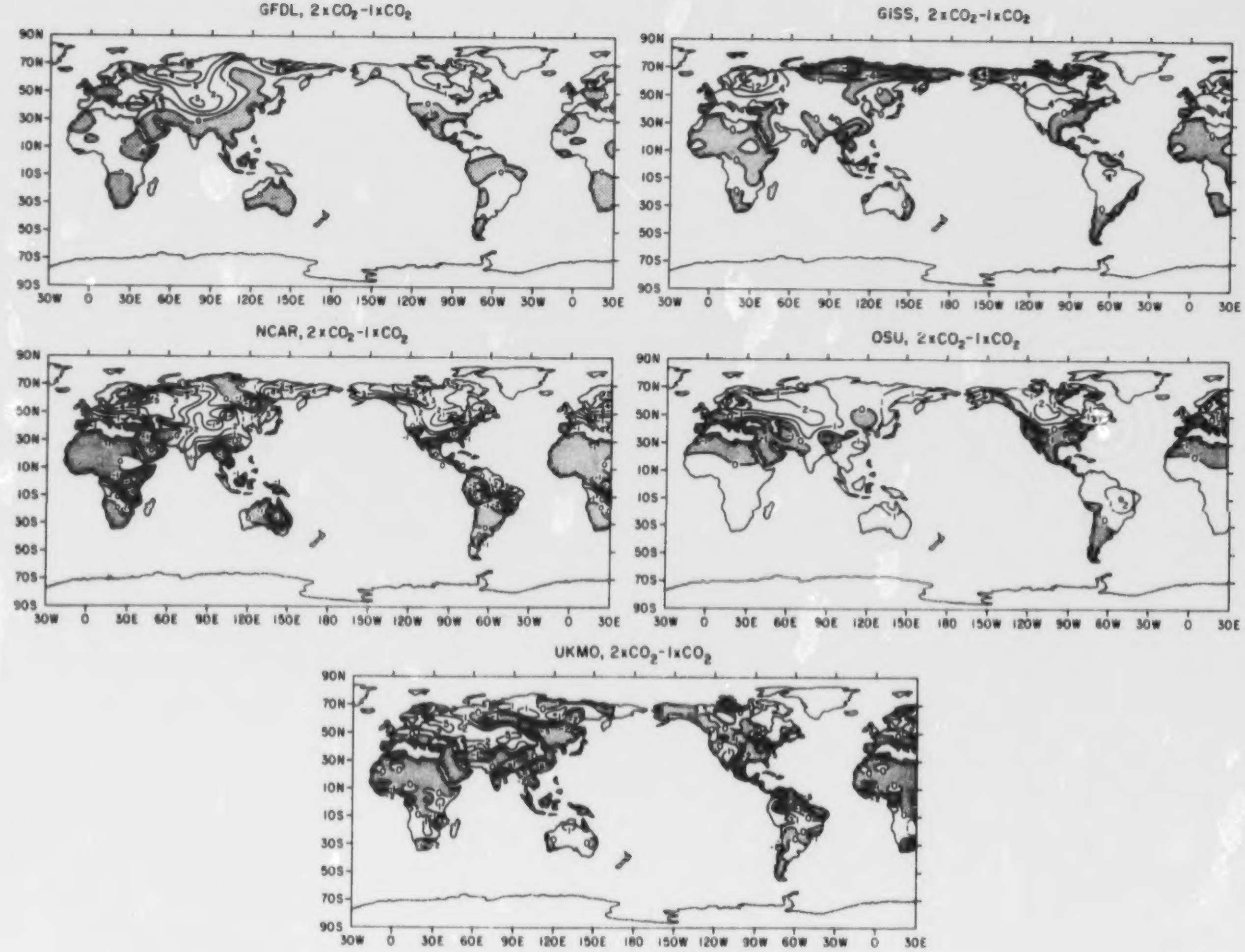
GFDL, $2 \times CO_2 - 1 \times CO_2$
GISS, $2 \times CO_2 - 1 \times CO_2$
NCAR, $2 \times CO_2 - 1 \times CO_2$
OSU, $2 \times CO_2 - 1 \times CO_2$
UKMO, $2 \times CO_2 - 1 \times CO_2$
90N
70N
50N
30N
10N
10S
30S
50S
70S
90S
30W
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
30E

Figure 8. Geographical distribution of the soil water change (cm), 2 x $CO_2$ - 1 x $CO_2$, for DJF simulated by: (a) the GDFL model by Wetherald and Manabe (1986); (b) the GISS model by Hansen et al. (1984); (c) the NCAR model by Washington and Meehl (1984); (d) the OSU model by Schlesinger and Zhao (1988); and (e) the UKMO model by Wilson and Mitchell (1987). Stipple indicates a decrease in soil water.

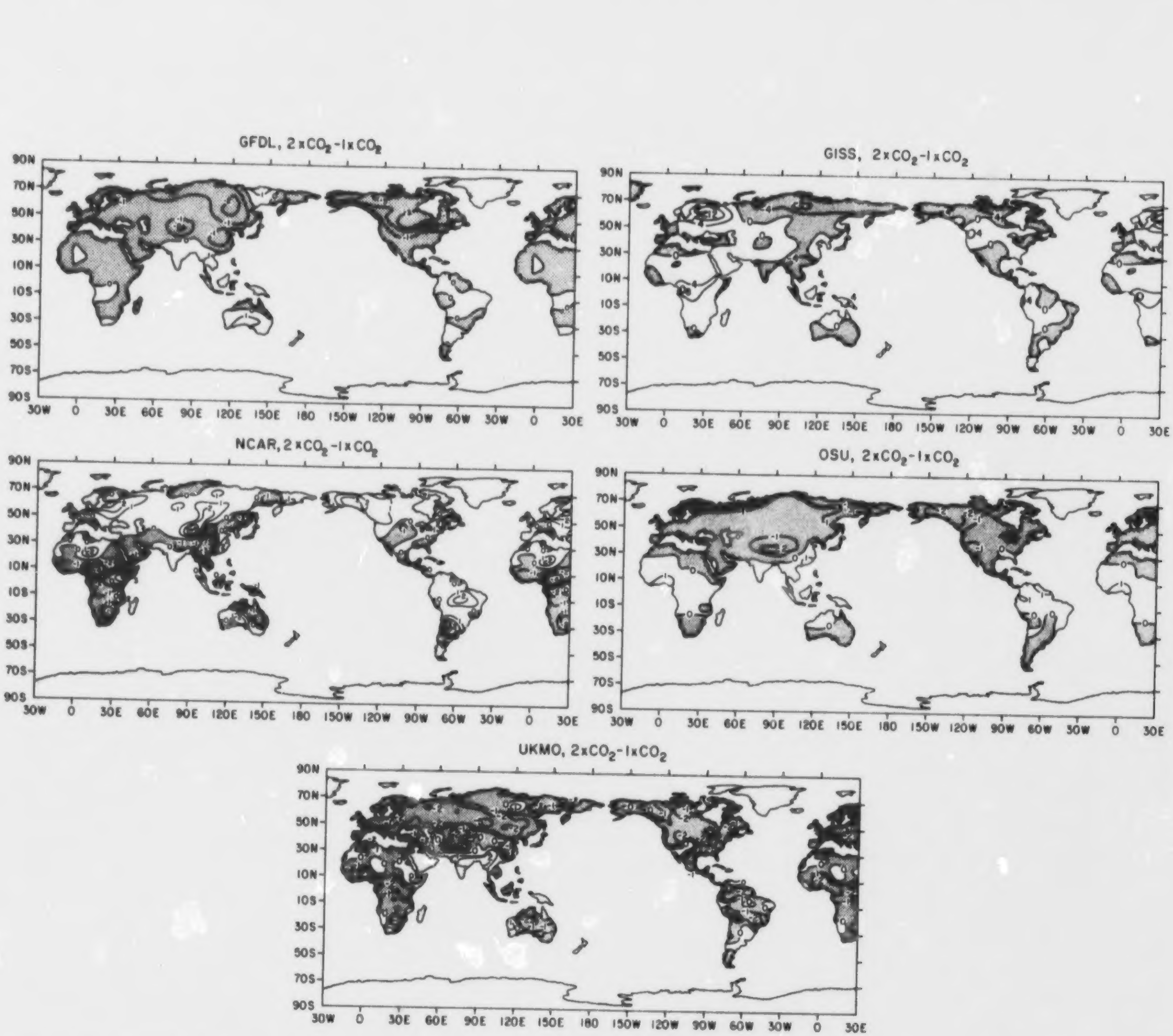
GFDL, $2 \times CO_2 - 1 \times CO_2$
GISS, $2 \times CO_2 - 1 \times CO_2$
NCAR, $2 \times CO_2 - 1 \times CO_2$
OSU, $2 \times CO_2 - 1 \times CO_2$
UKMO, $2 \times CO_2 - 1 \times CO_2$
90N
70N
50N
30N
10N
10S
30S
50S
70S
90S
30W
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
30E

Figure 9. Geographical distribution of the soil water change (cm), $2 \times CO_2 - 1 \times CO_2$, for JJA simulated by: (a) the GDFL model by Wetherald and Manabe (1986); (b) the GISS model by Hansen et al. (1984); (c) the NCAR model by Washington and Meehl (1984); (d) the OSU model by Schlesinger and Zhao (1988); and (e) the UKMO model by Wilson and Mitchell (1987). Stipple indicates a decrease in soil water.

where the direct radiative forcing $\Delta Q$ can be scaled to that for a $CO_2$ doubling, $\Delta Q_{2x}$, by (Augustsson and Ramanathan 1977)

$$\Delta Q = \Delta Q_{2x}\left[\frac{\ln[C(1984)/C(1861)]}{\ln 2}\right] ,$$

where C is the $CO_2$ concentration. Combining these equations and noting that $(\Delta T_s)_{2x} = G_f \Delta Q_{2x}$ gives

$$\Delta T_s = (\Delta T_s)_{2x}\left[\frac{\ln[C(1984)/C(1861)]}{\ln 2}\right] . \qquad (4)$$

If we assume that $(\Delta T_s)_{2x} = 4^oC$ based on the results from the GDFL, GISS, NCAR, OSU, and UKMO atmospheric GCM/mixed-layer ocean model equilibrium simulations, then for the $CO_2$ concentrations above, $\Delta T_s = 1.0^oC$. However, the reconstructed global-mean surface air temperature record (Jones et al. 1986) indicates a warming from 1861 to 1984 of about $0.6^oC$. Does this difference mean that the gain, $G_f$, of our climate models is about twice as large as that of nature. The likely answer is no, because the actual response of the climate system lags the equilibrium response due to the thermal inertia of the ocean. This can be illustrated by the energy-balance model

$$C_s \frac{d\,\Delta T_s}{dt} = \Delta Q - \frac{\Delta T_s}{G_f} ,$$

where $C_s$ is the heat capacity of the upper ocean. When equilibrium is achieved, $d\Delta T_s/dt = 0$ and $(\Delta T_s)_{eq} = G_f \Delta Q$, as in Equation (1). However, the transient solution

$$\Delta T_s(t) = (\Delta T_s)_{eq}\left(1 - e^{-t/\tau_e}\right)$$

shows that the equilibrium is approached exponentially with a characteristic "e-folding" time $\tau_e = C_s G_f$, which is the time required to reach $1 - e^{-1}$ or 63% of the equilibrium response. In the following, the studies of this lag of the climate system are reviewed.

## 3.1 RESULTS FOR AN ABRUPT $CO_2$ INCREASE

The transient response of the climate system to an abrupt $CO_2$ increase has been investigated with planetary energy-balance, radiative-convective, and simplified atmospheric general circulation models in conjunction with box-diffusion, box-upwelling-diffusion, and two-box ocean models. The box-diffusion ocean model consists of a fixed-depth, mixed layer (the box) surmounting the thermocline and deep ocean, in which vertical heat transport is treated as a diffusive process with a prescribed thermal diffusivity, $\kappa$. The box-upwelling-diffusion ocean model is a box-diffusion model with a prescribed oceanic upwelling velocity, W. The two-box ocean model comprises a fixed-depth, mixed-layer box and an intermediate-water box, which exchange heat vertically within a prescribed ventilation time. A transient simulation with a global, coupled atmosphere-ocean general circulation model has also been performed. In the following, the results of studies with these simple and more-comprehensive models are presented.

### 3.1.1 Results from Simplified Models

The results of six studies of the transient response to abrupt heating are presented in Table 3. Hoffert et al. (1980), using a box-upwelling-diffusion ocean model, and Schneider and Thompson (1981), using a two-box ocean model, obtained e-folding times of about 10 to 20 years. A slightly larger e-folding time of 25 years was obtained by Bryan et al. (1982) and Spelman and Manabe (1984). They used a simplified coupled atmosphere-ocean general circulation model in which the geographical domain was restricted to a 120° longitude sector extending from equator to pole, with the western half of the sector occupied by land at zero elevation and the eastern half by an ocean with a uniform depth of 5000 m. On the

Table 3. The e-folding time, $\tau_e$, for abrupt heating from selected climate model studies.

| Study | Model | $\tau_e$ (years) |
|---|---|---|
| Hoffert et al. (1980) | Planetary energy-balance climate model and a box-upwelling-diffusion ocean model | 8 to 20 |
| Schneider and Thompson (1981) | Planetary energy-balance model and a two-box ocean model | 13 |
| Bryan et al. (1982); Spelman and Manabe (1984) | Coupled atmosphere-ocean general circulation model with simplified geography and topography | 25 |
| Hansen et al. (1984) | Radiative-convective climate model and a box-diffusion ocean model | 27<br>55<br>102 |
| Bryan et al. (1984) | Global oceanic general circulation model | 100 |
| Siegenthaler and Oeschger (1984) | Planetary energy-balance climate model and a box-diffusion ocean model | 60 |

other hand, Hansen et al. (1984) used a box-diffusion ocean model and obtained 27-, 55-, and 102-year e-folding times corresponding to assumed climate system gains, $G_f$ of 0.465, 0.698, and 0.977$^oC/(Wm^{-2})$, respectively. Bryan et al. (1984) used an uncoupled global oceanic general circulation model and found an e-folding time of about 100 years in response to an imposed 0.5$^oC$ upper-ocean surface warming. Lastly, Siegenthaler and Oeschger (1984) obtained a 60-year e-folding time in their study using a box-diffusion model.

The studies presented in Table 3 indicate that the e-folding time $\tau_e$ lies between 10 and 100 years. If $\tau_e \approx 10$ years, then the actual response of the climate system would be quite close to the equilibrium response. Moreover, the disparity between the latter for the 1861 to 1984 warming and the corresponding observed warming would mean that the gain of our climate models is larger than that in nature. On the other hand, if $\tau_e \approx 100$ years, then the actual response of the climate system would be quite far from the equilibrium response, thus indicating that the gain of our climate models may be correct.

The factors that contribute to the wide range in $\tau_e$ have been discussed by Wigley and Schlesinger (1985) from their analytical solution for the energy-balance climate/box-diffusion ocean model. These authors found that $\tau_e$ depends quadratically on the climate system gain, $G_f$, and linearly on the thermal diffusivity, $\kappa$ . When a box-upwelling-diffusion model is used instead, the resultant e-folding time of the numerical solution can be expressed as shown on Figure 10 by

$$\tau_e = 92.57\ G^{1.93}\ \kappa^{0.94}\ \exp(-0.15\ G^{0.97}\ \kappa^{0.09}\ W^{0.78})$$

However, in view of this dependence of $\tau_e$ on $G_f$, $\kappa$ and W, quantities which are prescribed in an energy-balance climate model, the determination of whether $\tau_e \approx 10$ or 100 years requires a global, coupled atmosphere/cean general circulation model in which these quantities are self-determined. The results from a simulation with such a model are described below.

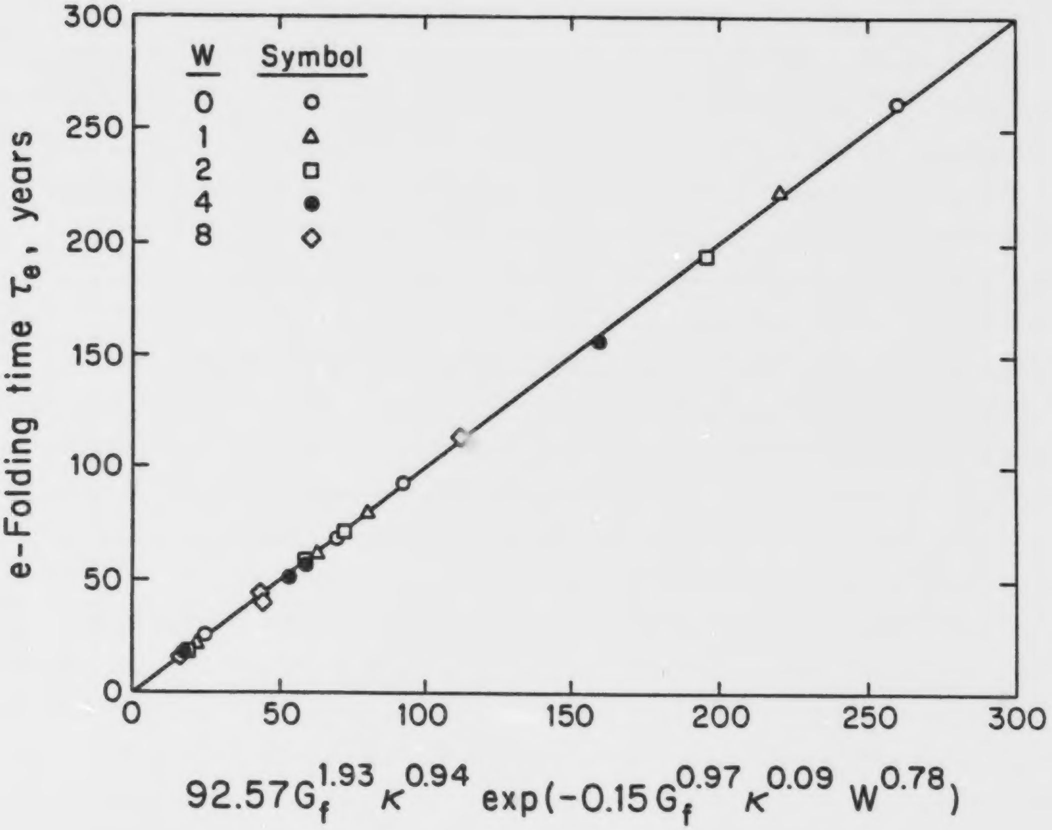

Figure 10. The e-folding time $\tau_e$ for an abrupt heating perturbation versus $92.57\ G_f^{1.93}\ \kappa^{0.94}\ \exp(-0.15\ G^{0.97}\ \kappa^{0.09}\ W^{0.78})$. The data points were obtained from a numerical solution of a box-upwelling-diffusion model for upwelling velocities $W = 0, 1, 2, 4$ and $8\ \mathrm{m\ yr^{-1}}$. The fit (straight line) was obtained by regression.

### 3.1.2 Results from a Global, Coupled Atmosphere-Ocean GCM

To investigate the transient response of the climate system, 1 x $CO_2$ and 2 x $CO_2$ simulations were performed with the OSU coupled atmosphere-ocean general circulation model (Schlesinger et al. 1985; Schlesinger and Jiang 1987). The atmospheric component of the coupled model is basically the two-layer AGCM described by Schlesinger and Gates (1980) and documented by Ghan et al. (1982). The oceanic component of the coupled model is basically the six-layer oceanic general circulation model (OGCM) developed by Han (1984 a,b), and extended by him to include the Arctic Ocean. The coupled model predicts the temperatures and velocities of the atmosphere and ocean, the atmospheric surface pressure and water vapour, the oceanic salinity, the land surface temperature and water content, the sea ice thickness, and the snow mass and clouds. It also includes both the diurnal and seasonal variations of solar radiation. The coupled model is global, has realistic continent/ocean geography and land and ocean-bottom topographies, and is integrated synchronously; that is, both component models simulate the same period of time. The 1 x $CO_2$ and 2 x $CO_2$ simulations differed only in their $CO_2$ concentrations (326 and 652 ppmv, respectively), both were started from the same initial conditions, and each was integrated for 20 years. The evolution of the difference between the 2 x $CO_2$ and 1 x $CO_2$ simulations thus represents the transient climatic change induced by an abrupt $CO_2$ doubling.

The evolution of the change in global-mean temperature induced by the doubled $CO_2$ concentration is shown in **Figure 11** in terms of the vertical distribution of monthly-mean 2 x $CO_2$ - 1 x $CO_2$ temperature differences for the atmosphere and ocean. The top panel of Figure 11 shows an initially rapid and vertically uniform warming of the atmosphere followed by a progressive slowing. The bottom panel of the figure also shows an initially rapid warming of the sea surface followed by a progressively slow warming. Figure 11 indicates that this decrease with time in the warming rate of the atmosphere and sea surface is the result of a downward transport and sequestering of heat into the interior of the ocean.

The temperature changes shown in Figure 11, when normalized by the equilibrium temperature change, define the climate response function for the

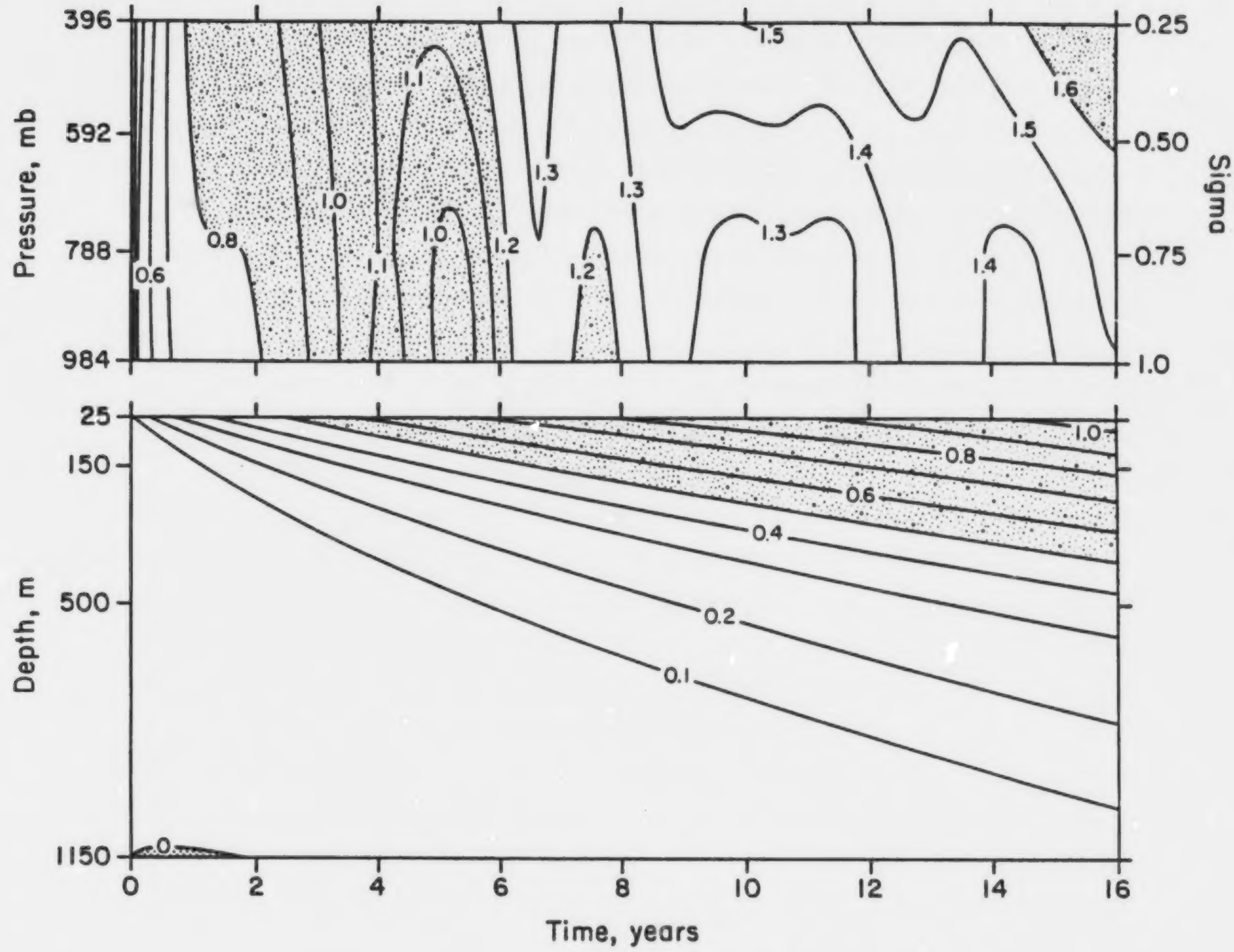

Figure 11. Latitude-vertical distribution of the 2 x $CO_2$ - 1 x $CO_2$ difference in the annual-mean, zonal mean temperatures ($0^oC$) of the atmosphere (above) and ocean (below) for year 16. Atmospheric warming larger than $1.6^oC$ is shown by light stipple, as is oceanic warming larger than $0.8^oC$, while oceanic cooling is indicated by heavy stipple. (From Scheslinger et al 1985.).

global-mean temperature. Clearly, these coupled atmosphere-ocean GCM simulations are not of sufficient duration for the equilibrium change to have been attained. However, an estimate of the equilibrium temperature change and the vertical transport characteristics of the ocean have been obtained from a representation of the time evolution of Figure 11 by a simple one-dimensional climate/ocean model (Schlesinger et al. 1985). An energy-balance climate/multi-box ocean model gives an excellent representation of the evolution shown in Figure 11, with self-determined parameters for which the estimated equilibrium temperature change is 2.8$^0$C. The effective ocean thermal diffusivity, $\kappa$, by which all vertical heat transport is parameterized in the simple multi-box ocean model representation, is 3.2 cm$^2$ s$^{-1}$ at the 50 m level, 3.8 cm$^2$ s$^{-1}$ at the 250 m level, and 1.5 cm$^2$ s$^{-1}$ at the 750 m level. The mass-averaged effective ocean thermal diffusivity of $\kappa = 2.25$ cm$^2$ s$^{-1}$ is in agreement with the best estimate based on the value required by a box-diffusion ocean model to reproduce the observed penetration of bomb-produced radionuclides into the ocean (Broecker et al. 1980; Siegenthaler 1983). Moreover, an energy-balance climate/box-diffusion ocean model with $\kappa = 2.25$ to 2.50 cm$^2$ s$^{-1}$ is successful in reproducing the evolution of the $2 \times CO_2 - 1 \times CO_2$ differences in the surface air and ocean surface layer temperatures simulated by the coupled atmosphere-ocean GCM. Consequently, it appears that the coupled model transports heat from the surface downward into the ocean at a rate which is commensurate with the rate observed for the downward transport of radionuclides.

The climate response function (obtained from the energy-balance, climate/multi-box ocean model representation of the coupled model, $2 \times CO_2 - 1 \times CO_2$ temperature evolution) is shown in Figure 12, where a projection with the simple model has been made to year 200 after the abrupt $CO_2$ doubling. It is seen that the response function is not simply $1-\exp(-t/\tau_e)$, as it would be if only the oceanic mixed layer warmed without transporting heat to the thermocline and deeper ocean. Thus, the response function cannot be characterized by a single parameter such as $\tau_e$. Nevertheless, the time to reach 63% of the equilibrium is useful for

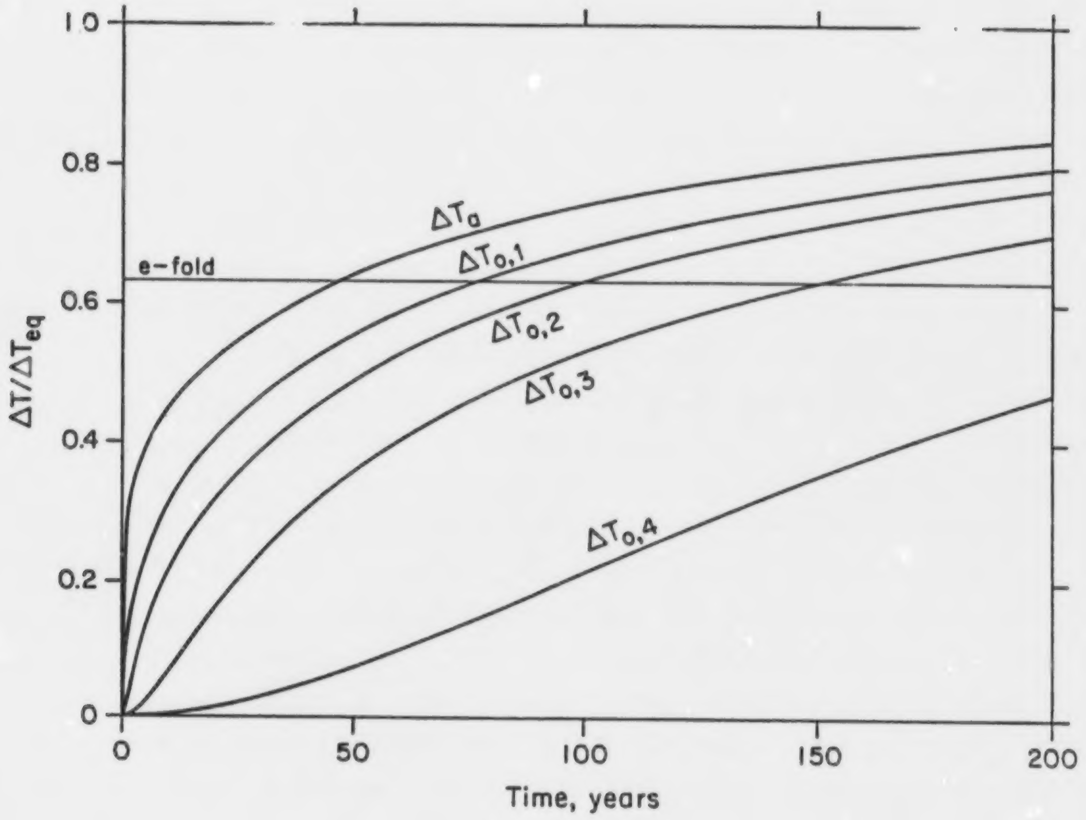

Figure 12. Energy-balance climate/multi-box ocean model projection to year 200 of the evolution of the 2 x $CO_2$ - 1 x $CO_2$ difference in global-mean surface air temperature [$\Delta T_a$ temperature ($\Delta T_{o,k}$, k = 1, 2, 3, 4) as a fraction of the equilibrium temperature difference ($\Delta T_{eq}$)]. The horizontal line labelled e-fold indicates the level at which $\Delta T/\Delta T_{eq}$ = 1-1/e ≈ 0.63. (From Schlesinger et al. 1985).

comparison with earlier studies (Table 3). Figure 12 shows that such an "e-folding" time is about 50 to 100 years.

## 3.2 RESULTS FOR A TIME-DEPENDENT $CO_2$ INCREASE

The results presented in the preceding section have been for the transient response of the climate system to an instantaneous doubling of the $CO_2$ concentration. However, the $CO_2$ concentration has not abruptly changed in the past, nor is it likely to in the future. Instead, the $CO_2$ concentration has increased more or less continuously since the dawn of the industrial revolution.

Hansen et al. (1984) and Wigley and Schlesinger (1985) estimated the temperature change from 1850 to 1980 that would be induced by the increasing $CO_2$ concentration during this 130-year period. Figure 13, based on the study of Wigley and Schlesinger (1985), in which the 1850 $CO_2$ concentration was taken as 270 ppmv, shows the 1850 to 1980 surface temperature change versus the equilibrium surface temperature change for a doubled $CO_2$ concentration. Again, let us assume that the latter is $4^oC$. If the climate system had no thermal inertia, the 1850 to 1980 surface temperature change would be in equilibrium with the instantaneous 1980 $CO_2$ concentration, and the warming would be given by an equation similar to Equation (4). As shown in Figure 13, this instantaneous equilibrium warming would be $1.3^oC$. However, when the heat capacity and vertical heat transport of the ocean are considered, as shown by the curves for the oceanic thermal diffusivities $\kappa = 1$ and $\kappa = 3\ cm^2\ s^{-1}$, the 1850 to 1980 warming is reduced to about 0.5 to $0.7^oC$, a range which does not conflict with the observational record. Consequently, it appears that the climate system gain of about $1^oC/(Wm^{-2})$, obtained by the most recent GCM equilibrium simulations, may be reasonably correct.

Figure 13 also shows that, even if the $CO_2$ concentration were to increase no further in the future, the Earth's surface temperature would continue to increase by about $0.7^oC$ in its approach to its new equilibrium value. This demonstrates the "Catch-22" nature of the $CO_2$-induced climatic change issue: The present warming is "small" and perhaps within the

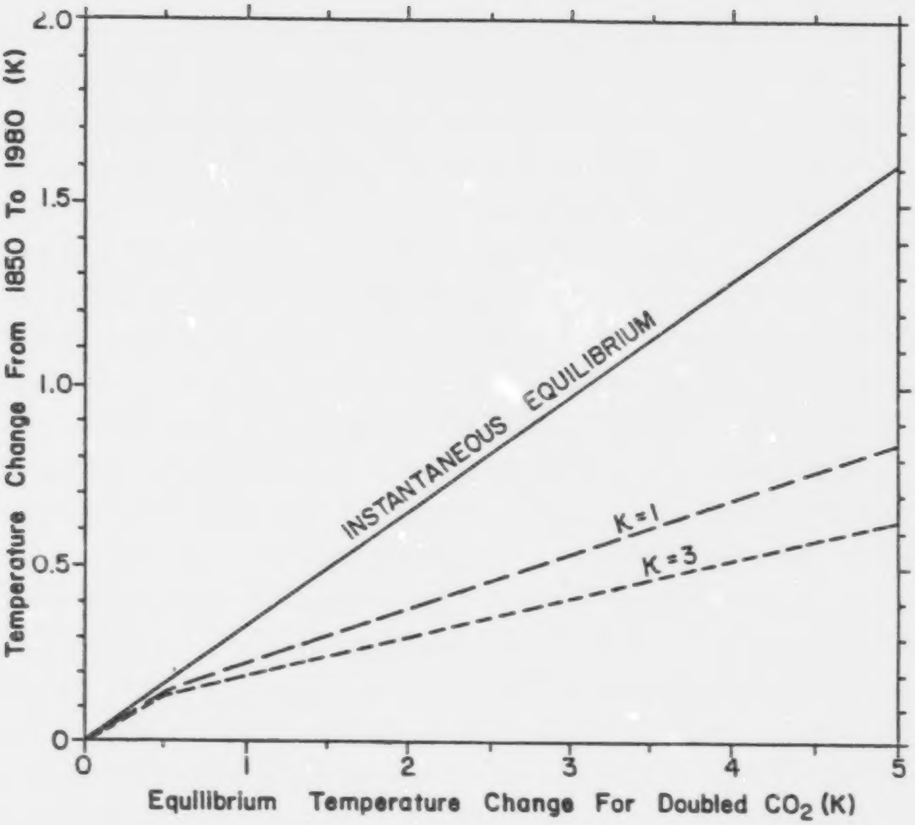

Figure 13. The temperature change from 1850 to 1980 versus the equilibrium temperature change for doubled $CO_2$. The instantaneous equilibrium curve is given by Equation (5). The curves $\kappa$ = 1 and $\kappa$ = 3 $cm^2$ $s^{-1}$ are from the results of Wigley and Schlesinger (1985).

natural variation of climate because the ocean sequesters heat within its interior, but because of this, when the warming becomes demonstrably evident, continued future warming is inevitable, even if the $CO_2$ concentration were prevented from increasing further.

## 4. SUMMARY

This paper has comprised a review of the simulations of $CO_2$-induced equilibrium and transient climatic change made by energy-balance, radiative-convective, and general circulation models. The equilibrium climatic change simulations have been characterized in terms of the direct radiative forcing of the increased $CO_2$, the response of the climate system in the absence of feedback processes, and the feedbacks of the climate system. The transient climatic change simulations have been characterized in terms of the e-folding time of the response of the climate system.

For a doubling of the $CO_2$ concentration, the direct radiative forcing is about 4 $Wm^{-2}$ for the surface-troposphere system. In the absence of feedbacks, the gain (output/input) of the climate system is about $0.3^oC/(Wm^{-2})$, and the change in the surface air temperature is therefore about $1.2^oC$. Surface energy-balance models (SEBMs) have given a warming of about 0.2 to $10^oC$ for a doubling of $CO_2$. This wide range is the result of the inherent difficulty in specifying the behaviour of the atmosphere in SEBMs. Radiative-convective models (RCMs) have given a warming of about 0.5 to $4.2^oC$ for a $CO_2$ doubling. This range is the result of water vapour feedback, lapse rate feedback, surface albedo feedback, cloud altitude feedback, cloud cover feedback, and cloud optical depth feedback. General circulation models (GCM) have given a warming of about 1.3 to $5.2^oC$ for a $CO_2$ doubling. This also is the result of the feedbacks listed above, except for that due to cloud optical depth feedback which has not yet been included in the GCM simulations of $CO_2$-induced climatic change.

The most recent simulations of $CO_2$-induced climatic change by the GFDL, GISS, NCAR, OSU, and UKMO atmospheric GCM/mixed-layer ocean models have been presented. The changes in the annual-mean, global-mean surface air temperature simulated by these models for a $CO_2$ doubling range from

2.8 to 5.2°C, and the corresponding changes in precipitation are from 7.1 to 15% of their 1 x $CO_2$ values. The $CO_2$-induced zonal-mean surface air temperature changes exhibit a seasonal variation which increases from the tropics toward the poles. The geographical distributions of the $CO_2$-induced temperature change display a warming virtually everywhere in both winter and summer. The warming is a maximum in the winter polar region where the 1 x $CO_2$ sea ice retreats poleward in the 2 x $CO_2$ simulation, and is a minimum in the summer polar region and in the tropics during both seasons. Over the continents, the $CO_2$-induced warming simulated by the models exhibits qualitative differences in seasonality and quantitative differences in magnitude. The geographical distributions of the $CO_2$-induced soil water change, simulated by all the models, reveal a moistening of the northern hemisphere continents in winter. A drying of much of the northern hemisphere continents in summer is simulated by the GDFL, OSU, and UKMO models, but not by the GISS and NCAR models.

The simulations of $CO_2$-induced transient climatic change by simplified models have given an e-folding time, $\tau_e$, of about 10 to 100 years for the response of the climate system to an abrupt increase in the $CO_2$ concentration. Simplified analytical and numerical analyses show that this wide range in the estimates of $\tau_e$ is the result of the dependence of $\tau_e$ on three parameters of the climate system; namely, its gain, the oceanic upwelling velocity, and the effective thermal diffusivity. A simulation with a global coupled atmosphere-ocean general circulation model indicates that $\tau_e$ is 50 to 100 years as a result of the transport of the $CO_2$-induced surface heating into the interior of the ocean. Theoretical studies for a time-dependent $CO_2$ increase between 1850 and 1980 demonstrate that this sequestering of heat into the ocean's interior is responsible for the concomitant warming being only about half that which would have occurred in the absence of the ocean. These studies also reveal that the climate system will continue to warm toward its as-yet unrealized equilibrium temperature change, even if there is no further increase in the $CO_2$ concentration.

## 5. CONCLUSION

The five most recent simulations of the equilibrium climatic changes induced by a doubling of the $CO_2$ concentration have been made with atmospheric general circulation models coupled to prescribed-depth, mixed layer models of the ocean. These ocean models do not include, in a physical way, the horizontal transports of heat, momentum, and salinity (see footnote 2), which are fundamental to the maintenance and change of the general circulation of the ocean. Therefore, such models cannot correctly simulate the sea surface temperature (SST) distribution which is of paramount importance for the general circulation of the atmosphere. Consequently, such atmospheric GCM/mixed-layer ocean models cannot correctly simulate the regional distribution of climate for either 1 x $CO_2$ or 2 x $CO_2$. Since only oceanic GCMs can simulate the horizontal and vertical transports upon which the SST and regional climates intimately depend, it is imperative that future simulations of $CO_2$-induced equilibrium climatic change be performed with coupled atmosphere-ocean GCMs.

A necessary condition for the acceptance of a coupled atmosphere-ocean model's simulation of a $CO_2$-induced equilibrium and/or transient climatic change is the validation of the model's simulation of the present (1 x $CO_2$) climate by comparing it with the observed present climate. A rudimentary model validation has been performed by Schlesinger and Mitchell (1985) for the 1 x $CO_2$ simulations by the GDFL, GISS, and NCAR models, and similar validations have been performed for the OSU and UKMO models by Schlesinger and Zhao (1988) and by Wilson and Mitchell (1987), respectively. These model validation studies show that, although the GCMs are the only type of model in the climate model hierarchy that can simulate climate on the regional scale, they do so not without error, particularly for the components of the hydrological cycle such as precipitation. Therefore, further improvement in the simulation of $CO_2$-induced climatic change requires the systematic analyses of the factors that contribute to the errors in the models' simulations of the present climate, and the subsequent correction of those errors. This will likely require the improvement of the methods used by the models for both the explicitly resolved and parameterized physical processes. The former can be done by comparing the solutions of the models' numerical methods with both exact solutions and the results of laboratory studies for simplified cases. The latter can be done with intercomparison studies among the models and observations following the approach of the Intercomparison of Radiation Codes in Climate Models (ICRCCM) program (Luther and Fouquart 1984).

The successful validation of a model's simulation of the present climate, while a necessary condition for the acceptance of its simulated $CO_2$-induced climatic change, is not a sufficient condition for this purpose. While in all likelihood such a sufficient condition does not exist, there is a second necessary condition; namely, that the model correctly simulate a climate different from that of the present. Thus, to increase confidence that the $CO_2$-induced climatic changes simulated by the models are correct at the regional scale, the model validation methodology described above for the present climate must also be applied to at least one other climate such as that of the Wisconsin Ice Age of 18 000 years before the present.

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# CLIMATE SIMULATION AND PREDICTION AT THE CANADIAN CLIMATE CENTRE

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## ABSTRACT

A review of the climate modelling research programme at the Canadian Climate Centre is presented. The two main General Circulation Model objectives of the programme are climate prediction and the quantification of man's influence on climate. These objectives are further divided into four streams of investigation on sensitivity studies, extended range forecasting, skill evaluations, ocean/atmosphere interactions, and $CO_2$ effect scenarios.

Future developmental activities concerning the coupling of ocean, ice, and atmospheric models are forthcoming. Proposed studies will concentrate on improved vertical and horizontal resolution, gravity wave drag formulations, interactive cloud and convective parameterizations, fuller stratospheric climate calculations and, improved transfer calculations.

The author concludes that, although General Circulation Models are complex, costly, and often perplexing, they remain the only foreseeable method of simulating and predicting the current and future behaviour of the climate system.

## 1. INTRODUCTION

The programme of research into climate simulation and prediction that is underway in the Canadian Climate Centre (CCC) is, with the exception of an effort to produce monthly forecasts by statistical/synoptic methods, focussed on the use of "general circulation" models of the atmosphere and ocean (Boer et al. 1984a, 1984b). These relatively comprehensive global models are based on the physical laws and mechanisms governing the climate system, albeit with various approximations.

The objectives of our research programme parallel, in a general way, those of the World Climate Research Programme (WCRP). The main objectives of that programme are to determine to what extent climate can be predicted and to determine the extent of man's influence on climate. As with the WCRP, the goals of our research effort may be roughly divided into three "streams":

1. Stream 1 is aimed at establishing the physical basis for the prediction of weather anomalies on time scales of one to two months,
2. Stream 2 is aimed at predicting the variations of the global climate over periods up to several years, and
3. Stream 3 is aimed at characterizing variations of climate over periods of several decades and assessing the potential response of climate to either natural or man-made influences.

Underlying the three streams is an implicit "Stream 0" activity, which includes the development and improvement of atmospheric and oceanic models needed to carry out the required research envisioned in the other streams. Stream 0 is aimed at establishing the physical basis for the current climate by reproducing that climate from "first principles" that are derived from the appropriate governing mathematical/physical equations. A description of the Canadian Climate Centre atmospheric general circulation model and a description of its simulated climate are given in Boer et al. (1984a,b).

## 2. TIME SCALES

Figure 1 indicates the time scales involved in various aspects of weather prediction and climate research. Within a relative times scale, three

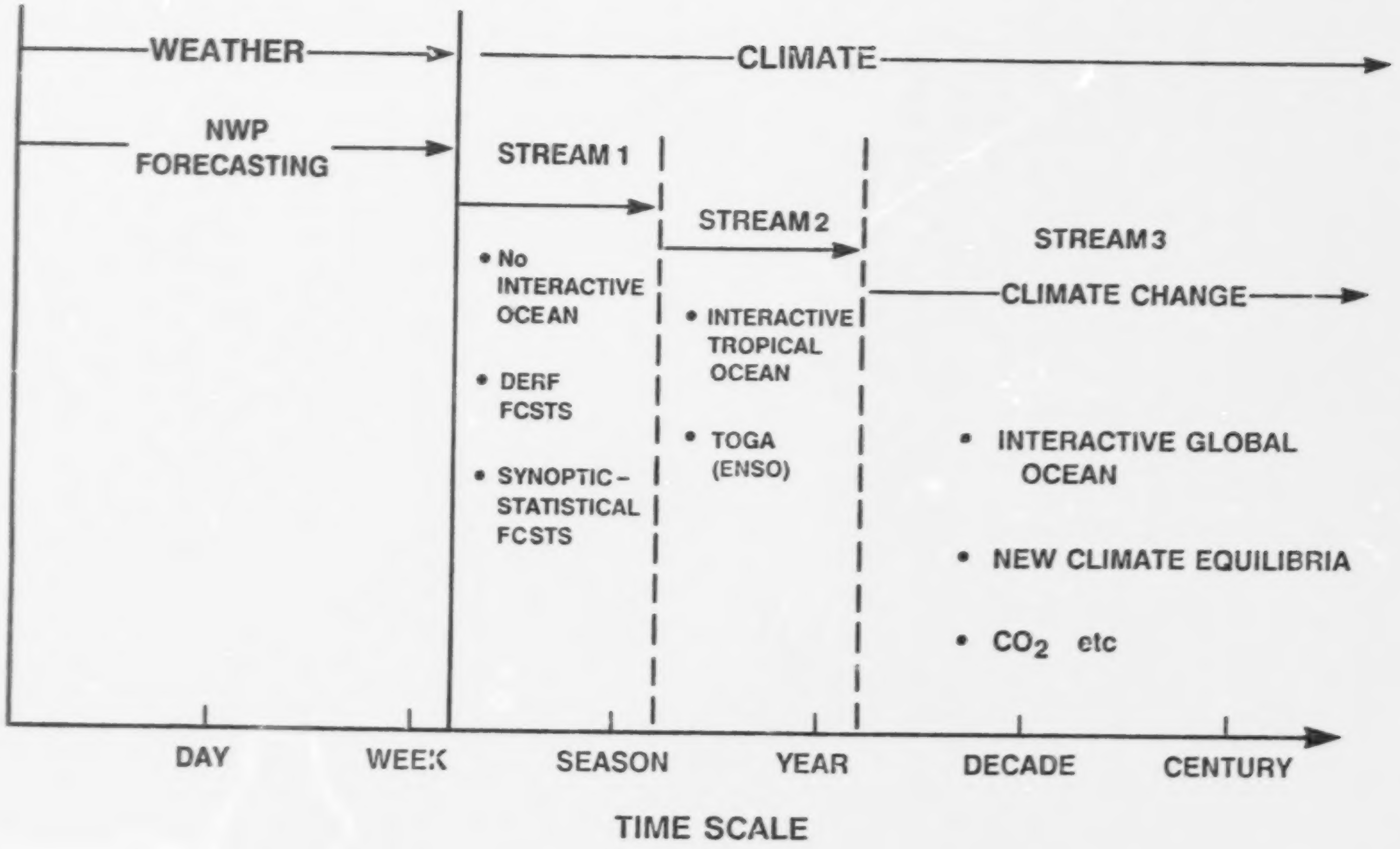
WEATHER
CLIMATE
NWP FORECASTING
STREAM 1
STREAM 2
STREAM 3
CLIMATE CHANGE
• No INTERACTIVE OCEAN
• DERF FCSTS
• SYNOPTIC-STATISTICAL FCSTS
• INTERACTIVE TROPICAL OCEAN
• TOGA (ENSO)
• INTERACTIVE GLOBAL OCEAN
• NEW CLIMATE EQUILIBRIA
• CO2 etc
DAY
WEEK
SEASON
YEAR
DECADE
CENTURY
TIME SCALE

Figure 1. Typical time scales of the climate problem.

streams of climate research can be identified, and several of their constituent activities can be highlighted. Time periods of less than about two weeks, which is the classical "deterministic predictability limit," are used by national and international numerical weather forecasting centres in their operational forecasting. Typically, these centres provide forecasts for periods that range from 1 to 10 days. The spatial resolution of forecast models is generally higher than that of climate models. Operational forecast models range from high-resolution, limited-area models (which are integrated for 1 or 2 days) to hemispheric models (which are integrated for up to 5 days) to global models (which are integrated for 10 or more days). Typically, longer forecast times are associated with larger computational domains and models with lower resolution, although this depends on the computational resources of the different meteorological services and centres.

## 3. ACTIVITIES UNDERWAY

### 3.1 MONTHLY AND SEASONAL TIME SCALES

Stream 1 activities are characterized by time scales of up to one season and by interactive coupling between the atmosphere and the land surface (Figure 1). No interactive coupling with the ocean is considered in this stream, although the ocean may affect the atmosphere through specified sea surface temperature anomalies (SSTAs), which, it is assumed, will persist for the period. Such studies consider atmospheric variation due to internal mechanisms and/or external forcing. Studies of the internal variability of the atmosphere (i.e., that which is not due to anomalous boundary forcing) show that potentially predictable, internal dynamic mechanisms exist in the model that may allow prediction of the (model) atmospheric state for extended periods.

Sensitivity studies of the atmospheric response to anomalous tropical sea surface temperatures have received considerable attention. These "El Nino" studies assume either a composite sea surface temperature anomaly or a particular SSTA such as that for 1982/83 and try to understand the resulting atmospheric response. The response of the model atmosphere to the comparatively large El Nino SSTAs of 1982/83 is discussed in Boer (1985), where it is shown that many of the features of the observed anomalous atmospheric behaviour are reproduced by the model.

Other Stream 1 activities involve experiments in Dynamical Extended Range Forecasting (DERF) using the Global Circulation Model (GCM). These forecasts are for periods of a month or a season but do not predict the day-to-day evolution of the atmospheric state, as do shorter-range forecasts. Rather, the attempt is to provide some information about the large-scale anomalies in temperature for a month. Long-range forecast skill may come from particularly stable flow situations or from long time-scale external forcing.

An ensemble forecast has been carried out for January 1983 under the presumption that the El Nino forcing of that period would provide a favorable circumstance for such a forecast. The anomaly correlation results for 10-day averages of 500 mb height in the northern extratropics suggest some skill for this case **(Figure 2)**.

A comprehensive DERF experiment is underway in which multiple, extended-range forecasts are being made under a variety of circumstances. This will provide information on the skill, or lack thereof, of forecasts based on general circulation models rather than the more usual forecasts at this range, which are based on statistical/synoptic approaches.

Statistical/synoptic monthly **(Figure 3)** and seasonal forecasts have been produced on an experimental basis in the Climate Centre for two years. Generally, the skill of the subjective forecast is rather low and, for the period in question, was slightly lower than persistence **(Figure 4)**, which is itself somewhat higher than normal for the period. A newer approach, termed "MOPP" (MOst Probable Pattern) results in an improved level of skill when applied retroactively to the period January 1986 to April 1987. Further tests in real time are necessary to see if the improvement will hold over the longer term. It is proposed to distribute these monthly forecasts of temperature anomaly in the near future as an operational product.

## 3.2 SEASONS TO YEARS

Stream 2 studies include time scales from seasons to years and involve interactive coupling with the tropical oceans (Figure 1). This coupling falls

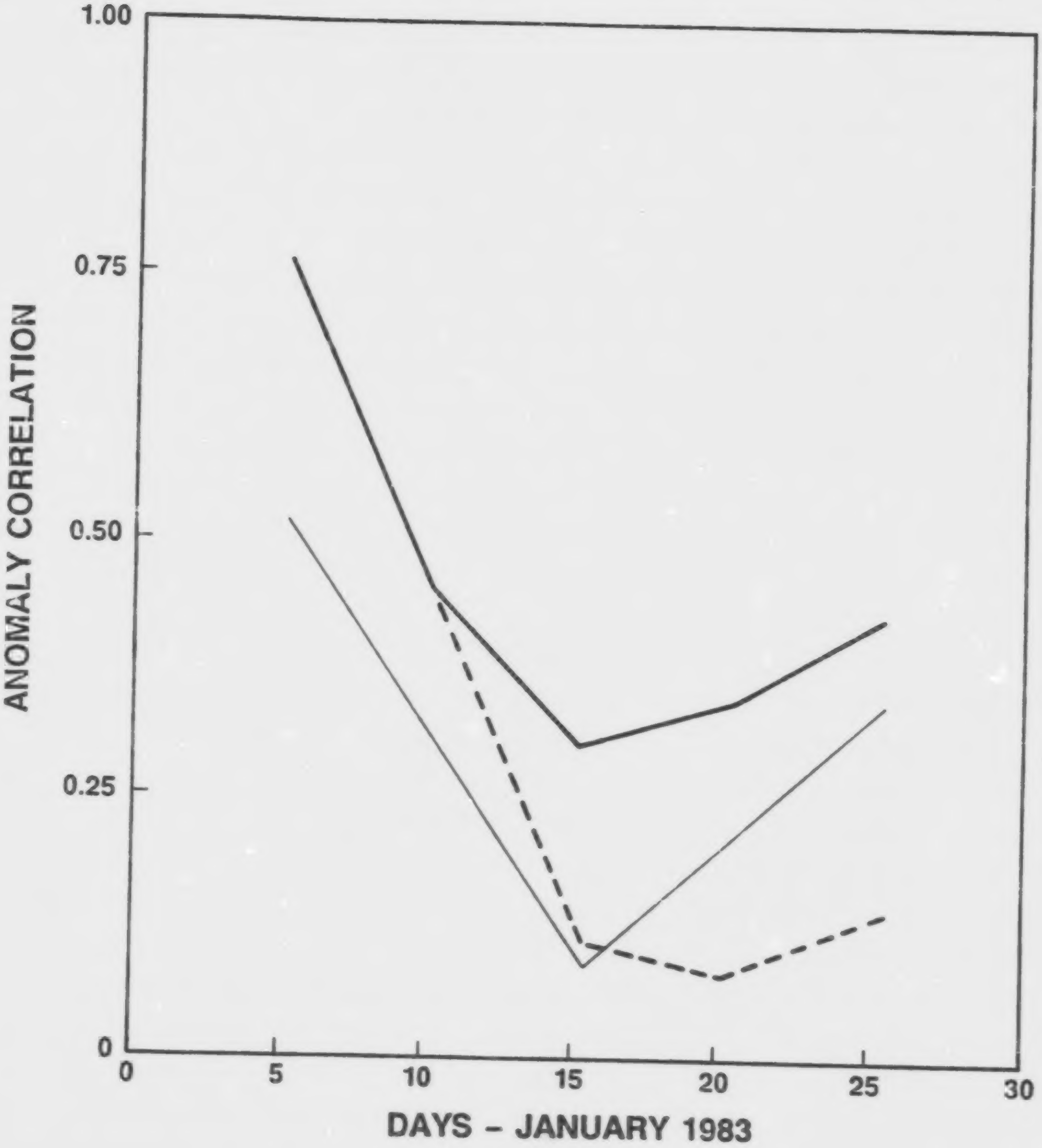

Figure 2. The anomaly correlation for overlapping 10-day mean 500 mb geopotential heights for the 30 to 90°N portion of the globe for January 1983 as a measure of skill for a DERF forecast with the GCM. (The dark solid line represents an ensemble forecast with the GCM; the dashed line represents the same forecast using climatological SSTAs rather than the El Nino SSTAs appropriate for that month. The light solid line is persistence.)

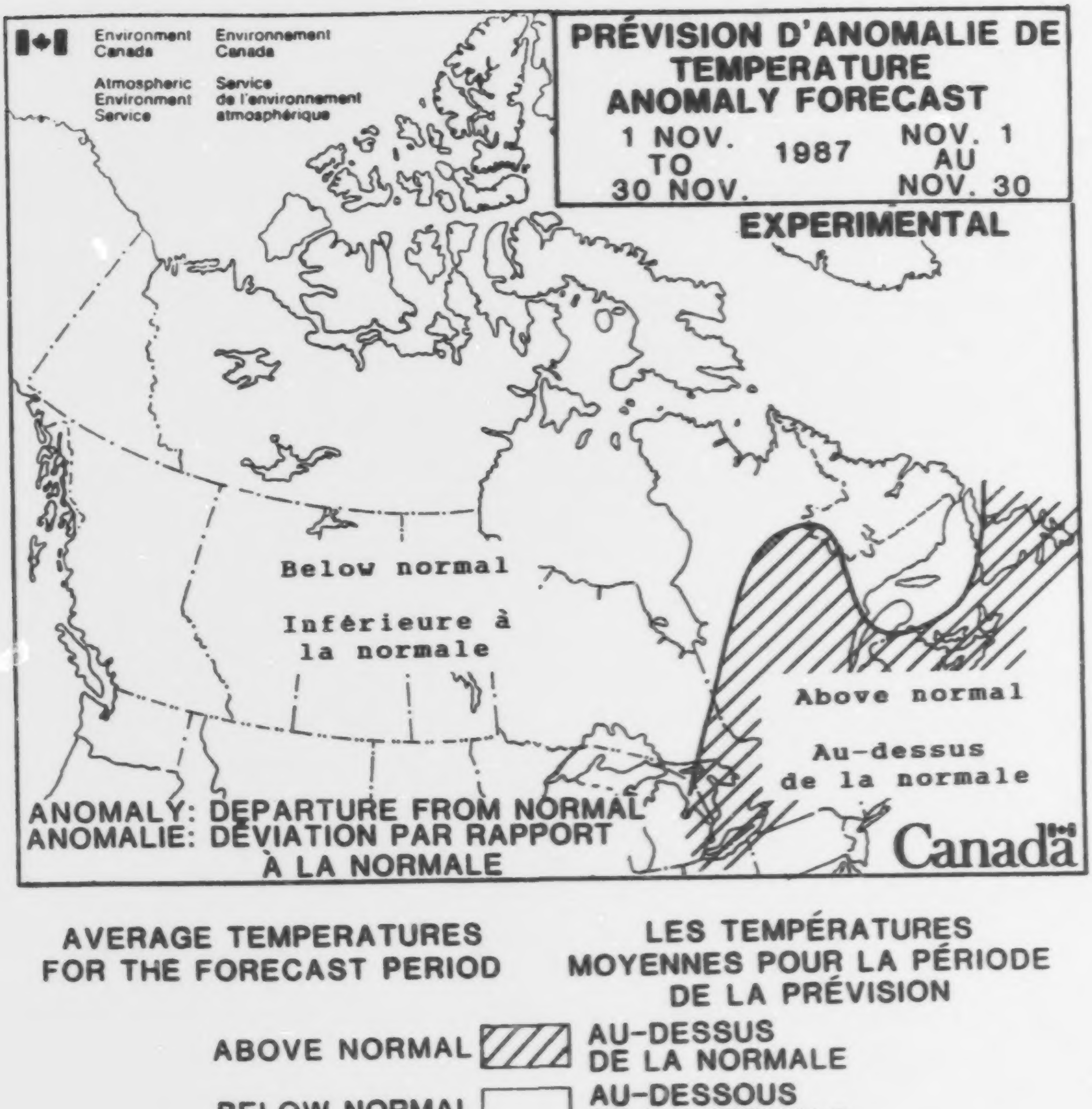
Environment Canada Environnement Canada
Atmospheric Environment Service
Service de l'environnement atmosphérique
PRÉVISION D'ANOMALIE DE TEMPERATURE
ANOMALY FORECAST
1 NOV. TO 30 NOV.
1987
NOV. 1 AU NOV. 30
EXPERIMENTAL
Below normal
Inférieure à la normale
Above normal
Au-dessus de la normale
ANOMALY: DEPARTURE FROM NORMAL
ANOMALIE: DÉVIATION PAR RAPPORT À LA NORMALE
Canada
AVERAGE TEMPERATURES FOR THE FORECAST PERIOD
LES TEMPÉRATURES MOYENNES POUR LA PÉRIODE DE LA PRÉVISION
ABOVE NORMAL ▨ AU-DESSUS DE LA NORMALE
BELOW NORMAL ☐ AU-DESSOUS DE LA NORMALE

Figure 3. A typical synoptic/statistical monthly temperature forecast product from the CCC.

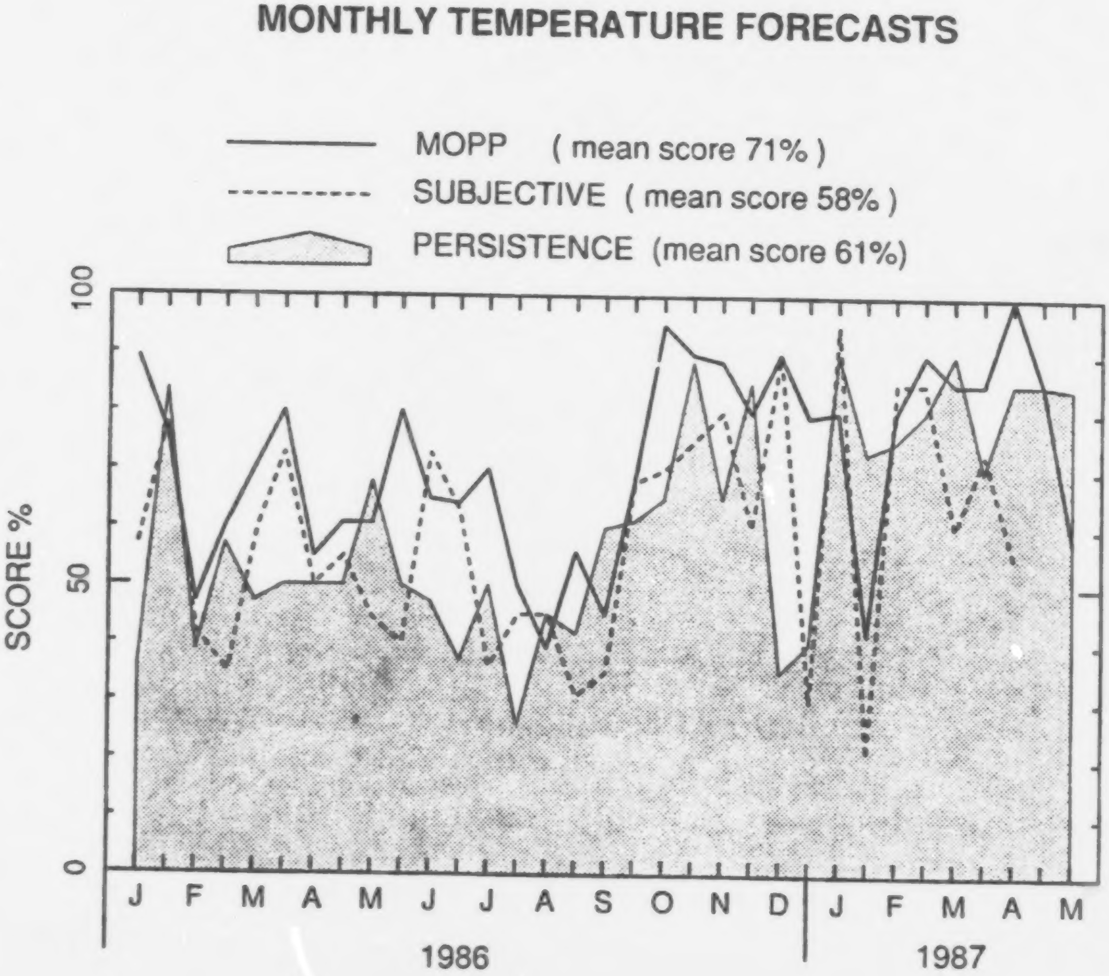

Figure 4. Time series of the scores of the MOPP and subjective monthly forecasts compared to persistence forecasts.

under the general heading of TOGA (tropical ocean/global atmosphere) and reflects our new knowledge concerning the behaviour of this coupled system. This ENSO, or El Nino/Southern Oscillation, mechanism involves the irregular appearance in the tropical oceans of anomalous temperatures, which have a major climatic effect in the tropical region and an important, but less dramatic, effect at extratropical latitudes.

The GCM has demonstrated that it responds in a reasonable fashion to the anomalous SSTAs of the 1982/83 El Nino. The anomalous wind stresses that result from the atmospheric model have been used to force a simplified tropical Pacific Ocean model. The ocean model, in turn, reproduces the observed SSTA to a reasonable degree. In other words, when integrated in an uncoupled fashion, both the atmospheric and simplified ocean models behave reasonably. This does not guarantee, however, that, when coupled together, the models will successfully simulate the ENSO. This is currently being tested by interactively coupling the atmospheric model to a simplified tropical Pacific Ocean model to assess the coupled model's ability to simulate and predict the ENSO-related interannual variability of the system.

### 3.3 YEARS TO CENTURIES

Stream 3 studies involve time scales of years to centuries and demand some sort of an interactive global ocean. The effect of double $CO_2$ concentrations on surface climate is perhaps the most notable aspect of the studies; however, the effects of other trace gases on the dynamics and photochemistry of the stratosphere are also important.

Current activities in Stream 3 studies consist of the improvement of version 1 of the model and its linking to a mixed-layer ocean and interactive ice model so that a $CO_2$ simulation may be carried out in the near future. Activities are also underway to revise the existing model to include a better stratospheric representation, with a view to future studies of the effects of trace gases on the stratospheric climate.

## 4. FUTURE ACTIVITIES

Currently, there is a wide range of atmospheric and oceanic models in use and under development at the CCC (Figure 5). The current CCC

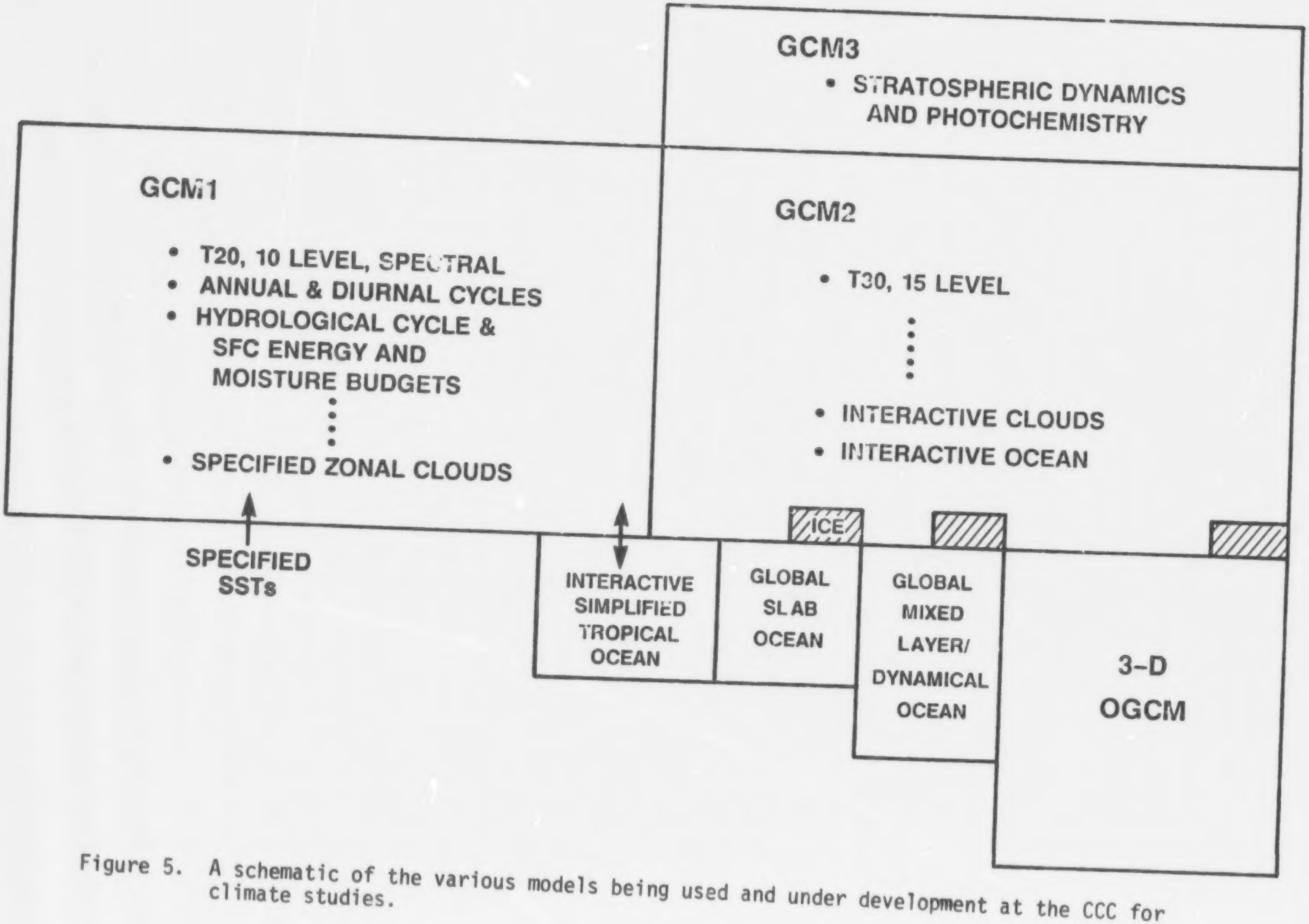
GCM3
• STRATOSPHERIC DYNAMICS AND PHOTOCHEMISTRY
GCM1
• T20, 10 LEVEL, SPECTRAL
• ANNUAL & DIURNAL CYCLES
• HYDROLOGICAL CYCLE & SFC ENERGY AND MOISTURE BUDGETS
• SPECIFIED ZONAL CLOUDS
GCM2
• T30, 15 LEVEL
• INTERACTIVE CLOUDS
• INTERACTIVE OCEAN
SPECIFIED SSTs
ICE
INTERACTIVE SIMPLIFIED TROPICAL OCEAN
GLOBAL SLAB OCEAN
GLOBAL MIXED LAYER/ DYNAMICAL OCEAN
3-D OGCM

Figure 5. A schematic of the various models being used and under development at the CCC for climate studies.

Atmospheric Global Circulation Model (AGCM) was one of the first to include both annual and diurnal cycles and to provide a good simulation of the climatology of both hemispheres. Some of the features of the model are indicated in this figure. This model has been used for a variety of studies of the present climate and perturbations thereto. They include the simulation of current climate and its natural variability, sensitivity studies to tropical sea surface temperature anomalies (El Ninos), study of climatic/ atmospheric mechanisms, and experiments in dynamical extended range forecasting. A partial list of GCM-related journal articles is given in the bibliography.

The coupling of GCM1 to a simple tropical Pacific ocean model for TOGA studies has commenced as mentioned above.

Version 2 of the AGCM features increased resolution in the horizontal and vertical, and improved radiative transfer calculations, gravity wave drag formulation, convective parameterization and interactive cloudiness, and surface budgets. Version 3 of the model will aim to include a fuller representation of processes affecting stratospheric climate.

A range of ocean models is under development at the CCC and at McGill University. In particular, a simple "slab" ocean and a thermodynamic ice model have been developed for the $CO_2$ simulation. Other more dynamical ocean models are being developed in conjunction with McGill University.

## 5. CONCLUDING COMMENTS

General circulation models of the atmosphere and the ocean are complex, cumbersome, costly, involved, intricate, and often perplexing. Nevertheless, they provide a physically based approach to understanding and predicting climatic change and variability. There are few alternatives to the (potential) power and consistency of this approach. Despite the difficulties in the development of these models and the current range of uncertainty in their simulations, they remain the only foreseeable method of obtaining the kind of information required to simulate and predict the current and future behaviour of climate systems.

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# APPLICATION OF CLIMATE MODEL OUTPUT TO IMPACT STUDIES: WATER RESOURCES

by

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## ABSTRACT

Global climate may experience significant warming in the next few decades because of increases in atmospheric concentrations of carbon dioxide and other trace gases. The possible impacts of this projected change in climate may be quite significant, but the quantitative assessment of such impacts, particularly at the regional scale, is still in its formative stage.

Atmospheric modellers and other researchers have provided a number of scenarios of the earth's future climate, using General Circulation Models (GCMs), historical analogues, and hypothetical cases. The application of these scenarios to regional impacts studies is the subject of this discussion. Methodological concerns include mismatch of scales, direct and indirect application of climate scenario data, interpolation problems, and estimation of parameters not available from the scenarios.

Impacts studies of water resources in the Great Lakes region are reviewed. These indicate that most scenarios of climatic warming would result in reduced net basin supply and soil moisture within the watershed. However, there are many uncertainties because of the above concerns, particularly regarding estimates of lake evaporation.

A new study of the Saskatchewan River basin is in progress. Although its objectives are similar to those in the Great Lakes study, differences in geography and climate will probably influence several components of this work. These include regional differences in rainfall/runoff relationships and the influence of snowmelt in the Rockies on net basin supply at the mouth of the basin in Manitoba.

## 1. INTRODUCTION

Doubling of atmospheric concentrations of $CO_2$ from pre-Industrial Revolution levels (270 to 290 ppm) is projected to occur in the middle of the 21st century (Kellogg and Schware 1981; WMO 1986). Increases in atmospheric concentrations of other radiatively active gases, such as methane, have also been observed and are likely to continue. The latter will accelerate the change in the atmosphere's radiation balance. As a result, the radiative equivalent of a 2 x $CO_2$ atmosphere may occur as early as the 2030s (WMO 1986). These changes are expected to cause a major global warming of 1.5 to 4.5$^{o}$C (U.S. NRC 1982; WMO 1986).

The above projection of climatic warming is based on the consensus of a number of atmospheric researchers who have performed "experiments" using global-scale General Circulation Models (GCM). Others have used historical analogues of warm periods for the same purpose, but these results tend to show weaker temperature increases, with some decreases at certain locations or seasons of the year.

Differences between the various scenarios of future climate are responsible for some of the uncertainty that prevails in any attempt to study the impacts of climatic change. However, there are other sources of uncertainty due to the incomplete knowledge of how the natural environment, the economy, and society in general interact with prevailing climate, and how these sectors would adapt to climatic change. The climatic change issue has forced researchers from many disciplines to reconsider the role of climate and climate information in their work. This fundamental shift in our view of the linkages between climate and the physical and human environments is still in its early stage. Workshops such as this are vital to the learning process. They enable us to become more aware of the potential significance of "greenhouse" warming.

As part of the learning process, it is necessary to discuss the application of climatic change scenarios to impacts modelling. In the case of water resources at the regional scale, how can a change in air temperature and precipitation for a few widely spaced data points be translated into changes in net basin supply, evaporation, or irrigation demand for a particular watershed? What are the problems that must be overcome when applying climatic change scenario data to regional impacts studies?

The purposes of this discussion are to:

1. Discuss a possible methodology for estimating the impacts of future climatic warming on regional water resources;
2. Review a case study of the Great Lakes region; and
3. Consider implications of previous studies on research in the Canadian prairies.

## 2. CLIMATIC CHANGE SCENARIOS

### 2.1 SCENARIOS FROM ATMOSPHERIC MODELS

Schlesinger and Boer provide detailed descriptions of atmospheric models elsewhere in these Proceedings. An extensive review of atmospheric models, including a number of GCMs, can also be found in MacCracken and Luther (1985).

Briefly, global scale GCMs represent an ambitious attempt to simulate global weather and climate patterns. Simpler atmospheric models, such as radiative-convective models and one- and two-dimensional energy balance models, do not include certain aspects of climate, such as horizontal transport of heat and land/sea contrasts. GCMs are three-dimensional integrations of the fundamental equations for conservation of momentum, heat, and moisture; all aspects of the climate system are included.

However, many assumptions and parameterizations are required which lead to uncertainties in the modelling process. As a result, GCMs do not perfectly simulate the present climate. There are differences among components of the various GCMs and subsequently their projections of future climates differ. When the initial parameterizations are modified by doubling atmospheric concentrations of $CO_2$, any errors in the initial models would probably occur in the 2 x $CO_2$ simulations.

Model output is generally expressed as anomalies from model generated "normals". However, at present, neither the 1 x $CO_2$ model run, nor the "normals", are in complete agreement with normals obtained from

Canadian and U.S. weather station data. In 1984, the Canadian Climate Centre produced modified scenarios by adding the 2 x $CO_2$ "effect" (i.e., 2 x $CO_2$ - 1 x $CO_2$) to normals estimated for each grid point from isoline maps based on actual station data. This was done for model output provided by the Goddard Institute for Space Studies (GISS) and the Geophysical Fluid Dynamics Lab (GFDL). The modified scenarios were used in the Great Lakes case study (Section 4) and in a number of others (Environment Canada 1987). These scenarios will also be used in a study of the Saskatchewan River basin (Section 5).

When applying these data, it is assumed that the changes from 1 x $CO_2$ to 2 x $CO_2$ correspond to climatic changes that could be expected due to the radiative equivalent of a doubling of $CO_2$. The use of current station normals, rather than model-generated "normals", is an attempt to build in features of the prevailing regional climate. Due to limitations in computer time and speed, physical parameterizations, and uncertainties in existing data sets, current GCMs do not permit detailed regional estimates (Schlesinger and Mitchell 1985). In addition, they are unable to provide details on small scale surface hydrology (Gleick 1987).

## 2.2 HISTORICAL ANALOGUES

An alternative approach to producing numerical models, such as GCMs, is to use past warm periods as analogues of a future warm climate. The fundamental assumption of historical analogues is that the general circulation system of the atmosphere will respond in a similar way to different forcing mechanisms, provided that the boundary conditions (oceans, land, and ice surfaces) remain the same. In the case of $CO_2$-induced climatic warming, the assumption is that when heat is added to the lower atmosphere the resulting changes in circulation patterns will be similar, irrespective of the cause of the heating effect (Palutikof et al. 1984). In other words, it doesn't matter if the heating occurs because of additional $CO_2$, increased solar radiation, or some other event.

The advantage of analogues, particularly those derived from recent instrumental records (as opposed to geological evidence, historical documents, or other proxy data sources) is that sufficient detail is available to produce seasonal scenarios for populated areas of individual continents. Unfortunately, such data may not be available for remote areas, such as the Canadian Arctic, where station records may be of relatively short duration. Another major disadvantage is that observed differences between recent warm and cold years are much smaller than the warming projected by GCMs. Palutikof et al. (1984) interpreted these scenarios as indicative of conditions during the early phase of $CO_2$-induced warming, rather than a doubling of $CO_2$ concentrations.

Using a similar approach, Brown and Walsh (1986) constructed a set of eight analogue scenarios of Canadian climate. These eight cases represent either blocks of years, or several individual years, in which the temperature difference between the warmest and coldest blocks or years were assumed to represent scenarios of future warming. Although annual temperatures increase in all eight cases, some scenarios exhibit cooling in individual seasons. By contrast, GFDL studies show summer cooling for only a few grid points north of 65°N. Otherwise, GCM results do not indicate cooling in any month.

## 2.3 HYPOTHETICAL SCENARIOS

Hypothetical warming scenarios can be defined at the discretion of the modeller. Generally, the practice has been to make these scenarios as simple as possible. For example, the modeller could assume that every month of the year experiences the same warming and change in precipitation. A recent study of a river basin in the western United States utilized 10 such scenarios, as well as GCM output (Gleick 1986).

As a tool for sensitivity analysis, hypothetical scenarios represent a useful baseline reference when a number of atmospheric models and analogues are being compared. For example, in terms of impacts on streamflow, it may be possible to say that a particular analogue is equivalent to a hypothetical warming of +1°C, with a 10% decrease in precipitation.

# 3. USE OF SCENARIOS IN IMPACTS MODELLING

## 3.1 MISMATCH OF SCALES

One problem that must be overcome when applying climatic change scenarios to regional impacts studies is the relatively coarse spatial resolution of the scenarios' outputs. For example, the GISS model's output was originally for $8^{o}$ x $10^{o}$ grid squares. Large subgrid, scale variation, particularly in precipitation, would be evident at most locations, particularly those with significant topographic variations, such as mountain ranges or coastal zones. The original GISS output has been modified (Bach 1988) to produce a denser array of grid points, $4^{o}$ x $5^{o}$, but the problem remains.

Considerable interpolation may be required in order to overcome the scenarios' coarse resolution. A recent study by Crowe (1985) used present normals from operating stations to estimate snowfall changes for 173 grid points in southern Ontario, although there are only 6 GISS grid points in or near the area. Interpolation using present normals forces us to assume that local synoptic conditions will not significantly change in the future (e.g., timing and frequency of weather types). Is it possible that the future regional climate will include fewer episodes of frontal passage and increased convective activity? Would that alter the spatial distribution of precipitation in this region?

Gates (1985) presents a general five-step approach to overcoming the above problem. The first three steps translate the results of large-scale GCM experiments into local climate statistics. Steps four and five involve modelling local impacts and aggregating their results onto larger scales (Figure 1). Step two, the large-scale to small-scale transition, requires the development of transfer functions, or interpolation techniques, as described above. Once such local climatic change data are available, though they cannot be "verified" in the strictest sense, they can be used to model local ecosystem (or watershed) response to the climatic change scenario (step three). Gates (1985) notes that these impact models will usually be specific to each locality and to each component of the local ecosystem.

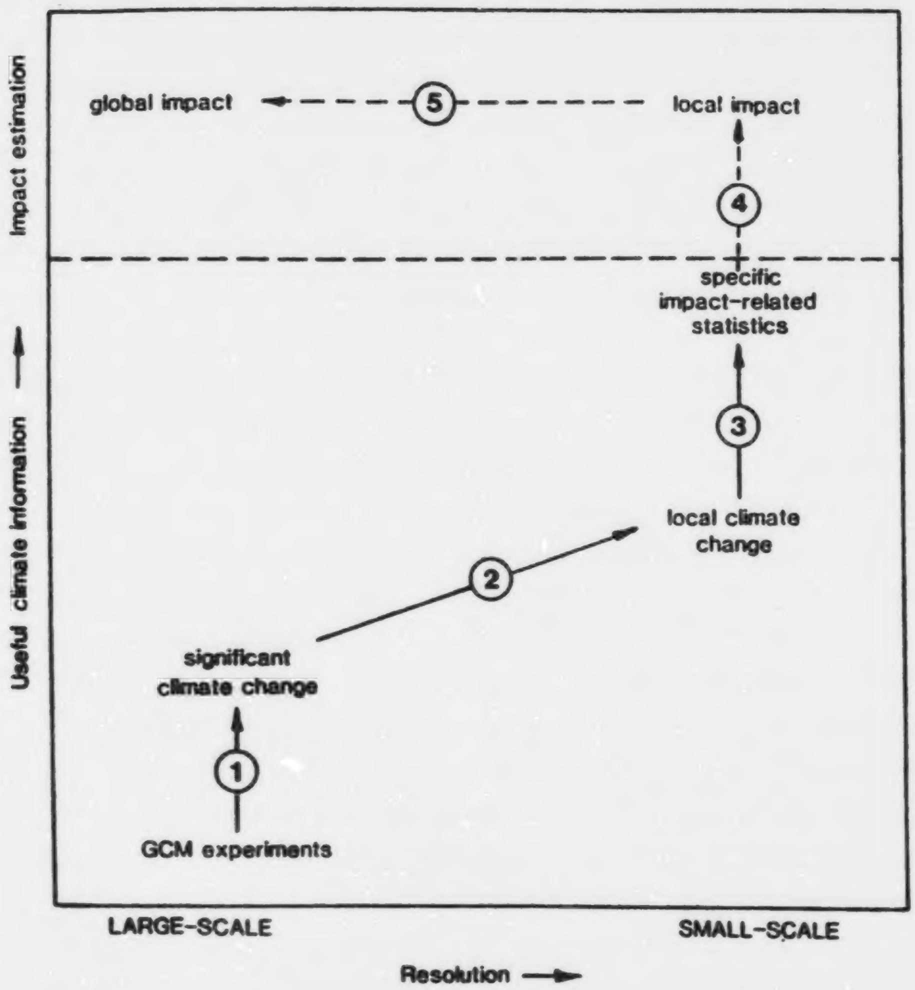
Impact estimation
Useful climate information →
global impact
5
local impact
4
specific impact-related statistics
3
local climate change
2
significant climate change
1
GCM experiments
LARGE-SCALE
SMALL-SCALE
Resolution →

Figure 1. Framework for estimation of ecosystem impacts of climatic change (Gates 1985).

Another important "mismatch of scales" is the fact that climatic events may not take place at the same temporal or spatial scale as social or ecological phenomena. Clark (1985) points out that certain ecological processes, such as vegetation range extension, occur at longer time scales and over smaller space scales than the projected "Greenhouse Effect" warming. Other processes, including biomass accumulation, occur on much shorter time scales and are, therefore, likely to adapt to prevailing conditions.

Impacts studies often proceed by imposing an instantaneous climatic change on present crops, vegetation, and socio-economic systems. Clark suggests that for processes that can adapt on a short time scale, such as crop growth, a more appropriate method for assessing the impacts of long-term climatic change would be to look at changes in indices of agricultural potential, rather than changes in the yield of specific crops. For slower ecological processes, Clark notes that the responses would probably lag behind the climatic warming scenario being considered here. Unlike the case of crop yields, the climatic change would be instantaneous relative to the rates of vegetation range extension.

Spatial and temporal scale problems in regional hydrology are likely to be dependent on the size of the watershed. For example, it is conceivable that under a climatic change scenario, small streams could experience a complete change in character, evolving from permanent to ephemeral or vice versa. Associated changes in vegetation would contribute to this evolution. Larger watersheds generally exhibit a more gradual response, but here, too, there could be changes in a variety of hydrologic variables, including soil moisture, extreme events, and the timing, location, duration, and extent of runoff (Gleick 1987).

Potential impacts on water resources planning and management differ from purely hydrological impacts; they require a different perspective. Beran (1986) points out that while all natural water is of hydrological interest, only water that is capable of exploitation (e.g., for shipping, hydropower, and irrigation) is of water resources interest. Given the present limitations of climatic change scenarios, the challenge in utilizing existing climate-hydrology-water resources transfer functions for impacts studies is to identify the scale problems pertinent to the watershed in question, and then determine procedures to overcome them. In addition, regional variations in physical geography, including climate, may influence the choice and application of hydrologic and impact models. Model validation exercises can be performed using present normal climate and streamflow data, but one cannot "validate" a streamflow projection based on a climatic change scenario. The alternative is to perform sensitivity studies, using a range of scenarios, to see if the watershed tends to respond in a particular direction.

## 3.2 ESTIMATES OF OTHER SURFACE ELEMENTS

Most scenarios provide monthly or seasonal projections on changes in temperature and precipitation. Changes in a large number of other elements can be obtained from GCMs, including wind, pressure, and humidity. Due to the lack of data in the instrumental record, all of these may not be available from the analogue scenarios, particularly in remote areas such as the Arctic. Analogues based on recent years (post-1945) are more likely to include such data, but the temperature anomalies from such a short period would be relatively small.

The above scenarios, after they have been modified by using normals based on station data, should contain features of the regional climate. These features would not appear in the GCM 1 x $CO_2$ model runs. However, there are certain elements that cannot be directly produced by the scenarios because of their coarse resolution. One example is lake temperature. In recent studies on water resources in the Great Lakes basin (Cohen 1986a, 1987b), it had been necessary to calculate evaporation loss for the five lakes. Projections of lake surface temperatures, a requirement of the evaporation model, could not be directly obtained from any scenario. Therefore, it was assumed that lake temperatures would increase at the same rate as the projected increase in air temperature from the nearest grid point. The exceptions were those months when the normal lake temperature was near 0.0°C, in which case, smaller increases were assumed. In the absence of more sophisticated techniques, this crude method appeared to be the only alternative available. Work in progress elsewhere (Irbe, personal communication) is focussing on using linear regressions with air temperature departures as the predictor. Preliminary results indicate that summer increases in Great Lakes water temperatures would actually be greater than projected air temperature increases, while winter changes would be similar to those described above.

Other elements that would probably require modifications include soil temperatures (due to variations in surface cover, aspect, and location of the water table), dew point temperatures and precipitation over large lakes, and ice cover. Unless there are physically based models available (site specific or otherwise), these elements can be estimated as above. For example, linear regression with air temperature has been used to estimate ice cover on the Great Lakes (University of Windsor 1986).

The case studies discussed in Sections 4 and 5 illustrate a number of problems encountered when applying scenario data on a regional scale.

# 4. POSSIBLE IMPACTS ON WATER RESOURCES IN THE GREAT LAKES BASIN

## 4.1 STUDY AREA

The Great Lakes Basin, which includes parts of Ontario and eight states in the U.S., has a drainage area of approximately 774 000 km$^2$, of which 32% is lake surface (Figure 2). Water flows from Lake Superior through the regulated St. Mary's River near Sault Ste. Marie. Lakes Michigan and Huron are both 7 m below Superior. The outflow of these three lakes proceeds through the unregulated St. Clair River and Lake St. Clair into Lake Erie, which drains into Lake Ontario via the Niagara River and the well-known Niagara Falls. Finally, water leaves the basin via the regulated St. Lawrence River at Cornwall. There it mixes with water from neighbouring basins as it proceeds toward the Gulf of St. Lawrence and the Atlantic Ocean.

Climatic variability has had a significant impact on mean annual Net Basin Supply (NBS) which is equivalent to the mean annual discharge at Cornwall. Above average basin precipitation since 1966 (Quinn 1981 and personal communication) has led to NBSs exceeding 8000 m$^3$/sec several times in the last 20 years (Figure 3). Record high lake levels occurred in 1986, causing flooding, erosion, and damage to shoreline property. Previously, in 1963 to 1965, low precipitation resulted in record low levels on some lakes,

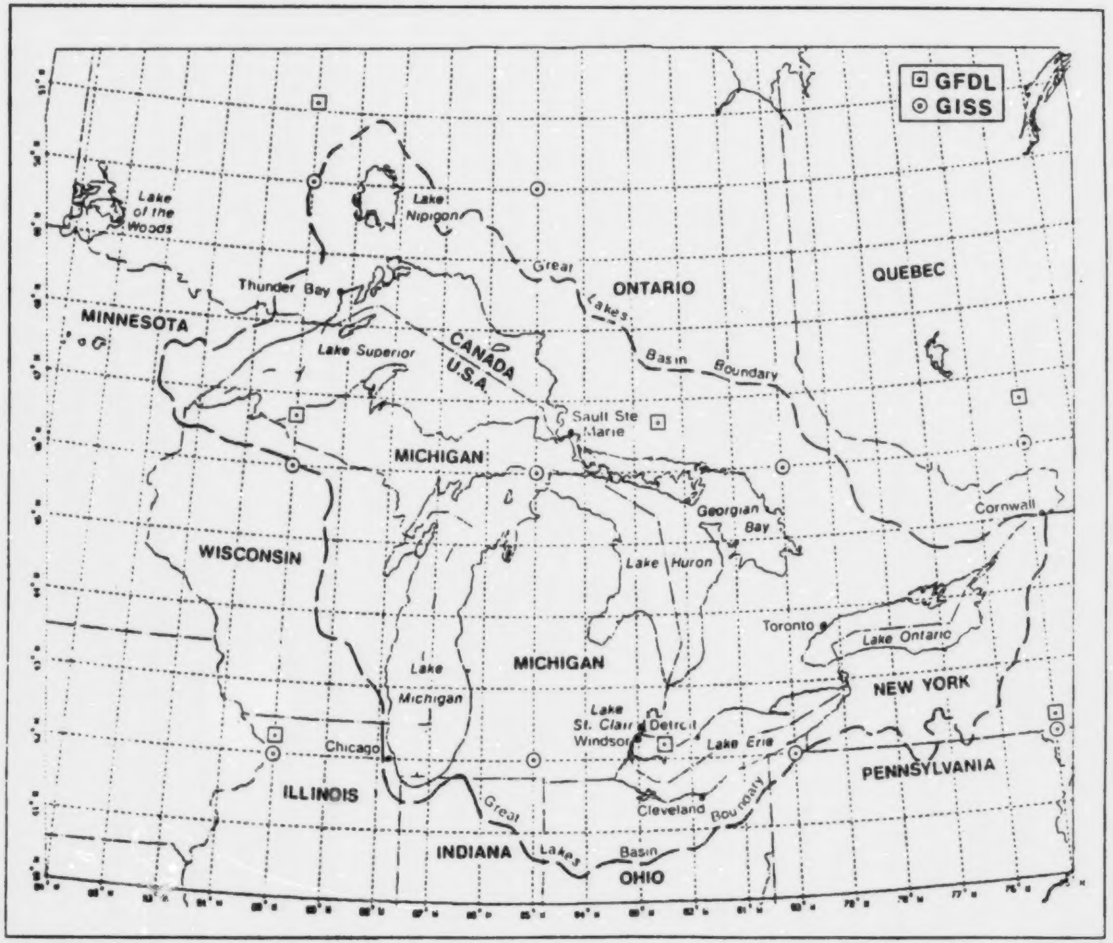
GFDL
GISS
Lake of the Woods
Lake Nipigon
Thunder Bay
MINNESOTA
Lake Superior
CANADA
U.S.A.
Great Lakes Basin Boundary
ONTARIO
QUEBEC
Sault Ste Marie
MICHIGAN
WISCONSIN
Georgian Bay
Lake Huron
Cornwall
Toronto
Lake Ontario
Lake Michigan
MICHIGAN
NEW YORK
Lake St. Clair
Detroit
Windsor
Lake Erie
Chicago
ILLINOIS
PENNSYLVANIA
Cleveland
INDIANA
OHIO

Figure 2. The Great Lakces basin, with grid points from two general circulation models (see Section 4). Source: Cohen (1986a).

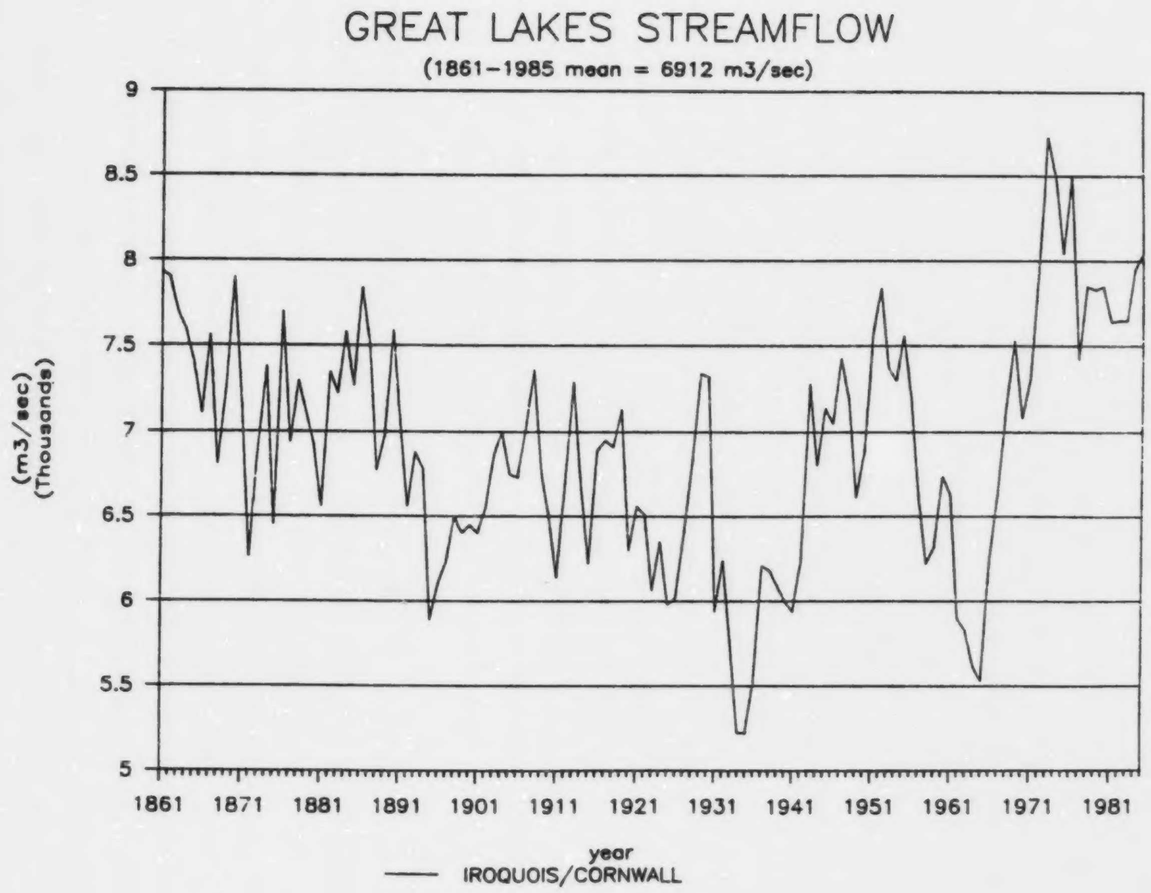

Figure 3. St. Lawrence River discharge measured at Iroquois (pre-1959) and Cornwall (1959 to present). Source: Environment Canada (1986).

causing losses to hydroelectric utilities and shipping companies, as well as to land-based activities, including agriculture (Allsopp et al. 1981). As the basin's water resources are exploited by many industries and a population of approximately 36 million people, there is considerable regional interest in lake levels and flows.

## 4.2 METHODOLOGY

In previous studies of the Great Lakes (Cohen 1986a, 1987b), NBS was determined as follows:

$$NBS = P_{(lake)} - E_{(lake)} + R + \text{diversions} - \text{consumptive use},$$

where $P_{(lake)}$ was overlake precipitation (mm), $E_{(lake)}$ was open water evaporation (mm), and R was overland runoff (mm). These were converted to $m^3$/sec. Groundwater was assumed to be of negligible importance at this scale. The net effect of existing diversions was a minor increase of less than 1% of "normal" NBS (1959 to 1985 "normal" = 7477 $m^3$/sec). Consumptive use was estimated at 106 to 180 m3/sec, or 1.4 to 2.4% of "normal" NBS (Cohen 1986b). Thus, the major elements influencing historical variations in NBS were $P_{(lake)}$, $E_{(lake)}$, and R. Diversions and consumptive use could play significant roles in the future if either or both increase in magnitude (Cohen 1986a, 1986b).

The procedure for computing NBS involved the application of two models: (1) the Thornthwaite climatic water balance (monthly version), and (2) a mass transfer approach for modelling vertical exchange of water vapour. These were utilized to estimate R and $E_{(lake)}$, respectively.

The Thornthwaite approach (Johnstone and Louie 1984; Mather 1978) estimates R and soil moisture deficit as residuals after accounting for precipitation and potential evapotranspiration, the latter being dependent on temperature and daylength. Actual evapotranspiration can be less than its potential due to insufficient water supplies (precipitation and soil moisture). Despite its empirical nature, the Thornthwaite approach has been found to provide reasonably reliable estimates of water balance components in most climates (Mather 1978), and it has been used in other impacts studies (e.g., Gleick 1986; Mather and Feddema 1986; Singh 1987). Beran (1986) points out that the water balance approach has an advantage over more complex "causal" models since it is relatively easy to make use of a wide range of climate scenarios. This provides the opportunity to do "comparative hydrology".

For this case study, it was assumed that soil moisture capacity was 100 mm and the minimum mean monthly temperature required for snowmelt was 0.0°C. The latter usually results in a one-month snowmelt peak during the first month in spring exceeding 0.0°C, which may be unrealistic in a hydrologic sense. However, the total annual snowmelt is probably not far off, thereby providing a reasonable basis for estimating annual R from both major sources, snowmelt and rainfall over land. It was also assumed that all land areas of the basin contributed to R. A weighted sum of R from all scenario data points was used to compute total basin R (Table 1). The weights were derived from the percentage of land area assigned to each point based on its location relative to neighbouring points. In Cohen (1987a), all scenario data were interpolated to the GISS grid point locations, so that the same set of area weights could be used in each case (results are discussed in Section 4.3).

The Thornthwaite model does not account for wind effects or the changes in transpiration rates that may result from higher $CO_2$ concentrations (Idso and Brazel 1984). Consequently, it is assumed that for a given water supply (precipitation and soil moisture), the relationship between transpiration and temperature will not change in a significant way.

The estimate of lake evaporation also included several assumptions. The mass transfer model (Quinn and den Hartog 1981; Richards and Irbe 1969) required an estimation of the vertical gradient in vapour pressure between the lake surface and the overlying air. Data on lake surface temperature, air and dew point temperatures above the lake surface, and wind speed were necessary inputs. Unfortunately, GCMs and other scenarios cannot directly provide these temperature data. In all climate scenarios, it was assumed that lake, air, and dew point temperatures would increase by the same amount as the projected increase in air temperature over land. An exception was months when present

Table 1. Effects of climatic change scenarios on annual water balance of the Great Lakes basin.

| Grid | Area | Precip[a] | | AE[a] | | Snowmelt[a] | | Runoff[a] | | Deficit[a] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | Weight | Norm[b] | $2CO_2$ | Norm[b] | $2CO_2$ | Norm[b] | $2CO_2$ | Norm[b] | $2CO_2$ | Norm[b] | $2CO_2$ |
| | | | | GISS: 4.3° to 4.8°C increase | | | | | | | |
| 1 | 0.071 | 735 | 835 | 461 | 550 | 200 | 245 | 274 | 286 | 12 | 14 |
| 2 | 0.051 | 791 | 888 | 438 | 525 | 317 | 218 | 353 | 363 | 28 | 30 |
| 3 | 0.133 | 878 | 960 | 539 | 650 | 224 | 148 | 339 | 310 | 2 | 11 |
| 4 | 0.167 | 777 | 835 | 493 | 585 | 195 | 113 | 284 | 249 | 42 | 69 |
| 5 | 0.159 | 963 | 1020 | 502 | 596 | 283 | 254 | 461 | 424 | 20 | 41 |
| 6 | 0.030 | 998 | 986 | 526 | 619 | 316 | 241 | 472 | 367 | 16 | 42 |
| 7 | 0.023 | 875 | 933 | 635 | 741 | 112 | 0 | 240 | 192 | 28 | 101 |
| 8 | 0.206 | 896 | 951 | 587 | 675 | 144 | 0 | 309 | 276 | 56 | 131 |
| 9 | 0.122 | 1017 | 1059 | 585 | 692 | 211 | 0 | 432 | 367 | 26 | 71 |
| 10 | 0.038 | 1170 | 1121 | 566 | 684 | 324 | 79 | 604 | 437 | 2 | 21 |
| Weighted Total | (1.000) | 895.4 | 952.6 | 533.1 | 629.8 | 217.5 | 117.7 | 362.3 | 322.7 | 28.7 | 62.1 |
| | | (+6.4%) | | (+18.1%) | | (-45.9%) | | (-10.9%) | | (+116.4%) | |
| | | | | GFDL: 3.1° to 3.7°C increase | | | | | | | |
| A | .072 | 754 | 811 | 457 | 505 | 251 | 233 | 297 | 306 | 5 | 12 |
| B | .162 | 821 | 817 | 524 | 560 | 243 | 135 | 297 | 256 | 6 | 51 |
| C | .251 | 847 | 862 | 480 | 524 | 303 | 256 | 366 | 338 | 39 | 81 |
| D | .034 | 1014 | 977 | 503 | 543 | 387 | 335 | 510 | 435 | 3 | 49 |
| E | .046 | 869 | 855 | 633 | 642 | 112 | 96 | 236 | 213 | 24 | 155 |
| F | .340 | 847 | 842 | 568 | 588 | 179 | 59 | 279 | 255 | 68 | 162 |
| G | .095 | 1148 | 1182 | 558 | 625 | 420 | 245 | 590 | 557 | 1 | 12 |
| Weighted Total | (1.000) | 871.4 | 878.2 | 530.6 | 565.9 | 252.6 | 162.1 | 340.5 | 312.6 | 35.5 | 94.5 |
| | | (+0.8%) | | (+6.7%) | | (-35.8%) | | (-8.2%) | | (+166.2%) | |

[a] Water balance terms in mm.

[b] Normals differ because the grid points are not in the same locations in each model's network.

Source: Cohen (1986a)

normal lake temperatures were near 0.0°C. In these cases, the increase in lake temperature was assumed to be less than the change in air temperature.

The increased dew point assumes an increase in atmospheric vapour pressure. Since lake temperature increases by the same amount, the absolute magnitude of the vertical vapour pressure gradient would also increase slightly. There would be greater evaporation loss in some months, but greater condensation in months when the air is warmer than the underlying lake surface.

## 4.3 RESULTS

NBS results for 140 scenarios, derived from GCM outputs, historical analogues, and hypothetical cases, are shown in Table 2. Column headings refer to 7 wind speed and vapour pressure scenarios, in which model or hypothetical changes were superimposed on the temperature and precipitation projection of 20 "base case" scenarios. The vapour pressure scenarios were applied to the already modified dew point temperatures. Since no additional changes have been imposed on lake temperatures, the vertical vapour pressure gradient changes significantly.

All these are warming scenarios, but the temperature increases of the analogues are weaker than the GCMs. Precipitation is above present normals for most months in the GCMs, but is generally below present normals in the analogues (e.g., Cohen 1987b).

The "N/N" column represents the 20 scenarios without any changes in wind speed and vapour pressure. Both GCMs and six of the eight historical analogues (HISTA to HISTE4) projected decreases in NBS. The hypothetical scenarios (2°C or 4°C warming each month, -20% to +20% change in monthly precipitation) show that in order for NBS to remain the same as present normals, an increase in precipitation is needed to offset the warming trend.

The other columns show the importance of lake evaporation in this study. In particular, the hypothetical 10% changes in vapour pressure lead to significant departures from the N/N projections. Prevailing theory suggests that the global temperature increases will be accompanied by increased atmospheric vapour pressure and relative humidity because of higher, global scale evaporation (Schlesinger and Mitchell 1985). Table 2 suggests that a

Table 2. Projected percent change in Net Basin Supply (NBS) in the Great Lakes under various climatic change scenarios. Consumptive use not included. Normal=7477 $m^3s^{-1}$.

| SCENARIOS | N/N | -20%/N | GFDL/N | N/+10% | N/-10% | GFDL/+10% | GFDL/-10% |
|---|---|---|---|---|---|---|---|
| GISS | -23.6 | -7.0 | -20.0 | 3.9 | -51.1 | 6.7 | -47.5 |
| GFDL | -16.9 | -2.7 | -14.0 | 8.5 | -42.3 | 11.3 | -39.2 |
| HISTA | 6.2 | 19.2 | 8.3 | 24.7 | -14.9 | 29.3 | -12.6 |
| HISTB | -16.1 | -3.3 | -14.1 | 5.2 | -37.4 | 7.0 | -35.2 |
| HISTC | 1.5 | 14.2 | 3.5 | 24.5 | -21.4 | 23.7 | -19.2 |
| HISTD | -16.4 | -3.8 | -14.4 | 4.5 | -37.3 | 6.4 | -35.1 |
| HISTE1 | -8.9 | 4.8 | -6.1 | 13.1 | -30.3 | 15.3 | -27.5 |
| HISTE2 | -26.5 | -14.0 | -24.4 | -5.9 | -47.1 | -4.0 | -44.8 |
| HISTE3 | -24.0 | -11.2 | -21.8 | -2.9 | -45.1 | -0.9 | -42.6 |
| HISTE4 | -8.8 | 4.2 | -6.4 | 12.4 | -30.0 | 14.5 | -27.3 |
| T2/-20P | -58.2 | -44.5 | -55.6 | -34.9 | -81.4 | -32.6 | -78.6 |
| T2/-10P | -36.3 | -22.6 | -33.7 | -13.0 | -59.5 | -10.7 | -56.7 |
| T2/N | -12.5 | 1.1 | -9.9 | 10.7 | -35.8 | 13.1 | -32.9 |
| T2/+10P | 12.1 | 25.8 | 14.7 | 35.4 | -11.1 | 37.7 | -8.3 |
| T2/+20P | 37.7 | 51.3 | 40.2 | 60.9 | 14.4 | 63.3 | 17.2 |
| T4/-20P | -70.9 | -55.9 | -68.0 | -44.4 | -97.5 | -41.7 | -94.3 |
| T4/-10P | -50.4 | -35.4 | -47.5 | -23.9 | -77.0 | -21.2 | -73.8 |
| T4/N | -28.4 | -13.3 | -25.5 | -1.8 | -54.9 | 0.8 | -51.7 |
| T4/+10P | -4.7 | 10.4 | -1.8 | 21.8 | -31.3 | 24.5 | -28.1 |
| T4/+20P | 19.7 | 34.8 | 22.6 | 46.3 | -6.8 | 48.9 | -3.9 |

Source: Cohen (1987b).
Column headings=u/VP. Row headings=T/P. N=normal.
T2,T4=temperature increase (C). P=precipitation change (%). See text for further explanation.

global increase in vapour pressure superimposed over the Great Lakes would reduce the loss in NBS because of reduced lake evaporation. However, the scenario of 10% change may be too large, or there may be unaccounted factors such as a feedback effect on local cloud cover, lake effect precipitation, and lake surface temperature, which also might influence NBS. More research is needed to derive accurate regional wind humidity and water temperature scenarios for large lakes within the context of the Greenhouse Effect.

Air temperature and precipitation data alone are not enough to completely answer all the questions about the impacts of future climatic warming in the Great Lakes. However, these results do seem to point toward a decrease in NBS. Further, a study of soil moisture deficit, using the same 20 "base case" scenarios and the Thornthwaite model, showed that 18 of the 20 scenarios would lead to increased summer deficits (Cohen 1987b). Another element in the NBS model, consumptive use, may also increase because of climatic warming. Research in this area has been hampered by lack of time series data on irrigation. Preliminary results for the municipal sector point to some increases (Cohen 1987a), but further transfer function development is required.

Despite the described uncertainties, these results may have an impact on policy-makers' awareness of the potential implications of an environmental change that might occur in just a few decades. A joint Canada-U.S. workshop on climate impacts in the Great Lakes is being planned for September 1988. The organizational committee includes representatives from Canadian and U.S. Climate Programs, and the U.S. Environmental Protection Agency. Climatic change is also being considered by the International Joint Commission in an ongoing assessment of lake levels. A report is expected in 1991.

## 5. A NEW CASE STUDY: THE SASKATCHEWAN RIVER BASIN

A study of the Saskatchewan River basin is now underway. As of September 1987, the project is still in the preliminary stages of methodological development and data collection. The basic objective is the same as for the Great Lakes study: to determine the possible impacts of projected climatic warming on NBS. Changes in NBS could have serious implications for agriculture, hydroelectric utilities, and a variety of other water uses. A recent study has already projected major declines in soil moisture in the basin, which would lead to summer warming of up to 9°C (Manabe and Wetherald 1986). At this point, it is appropriate to consider whether any modifications in approach are needed to account for differences in prevailing climate and hydrology between the Saskatchewan River and Great Lakes basins.

The Saskatchewan River basin has a drainage area of 364 239 km$^2$ (Figure 4). The study will focus on streamflow at The Pas, Manitoba, since data are more reliable there than at the basins' mouth. The study area will thus cover 347 267 km$^2$, or 95.3% of the basin.

An important feature of the study area is the fact that only about 1.5% is open water. Therefore, it is probable that changes in lake evaporation and overlake precipitation will be of minor importance to NBS. On the other hand, due to irrigation demand, consumptive use is already of great significance. A climate-irrigation transfer function should be developed, particularly oriented toward climatic water deficit as a predictor. Studies of municipal use of the Great Lakes showed that significant correlations could be obtained between consumptive use and water deficit, but it is inadequate as a predictor unless it can be weighted by temperature. Cohen (1987a) showed that similar deficits occurring during anomalously warm and cold summer months resulted in very different rates of municipal water use. It is possible that this could apply to irrigation demand as well.

The Thornthwaite approach should still be appropriate for predicting overland runoff. However, much of the basin's NBS originates as snowmelt from the Rocky Mountains. The contribution of overland runoff from the rest of the basin is quite low, due to low soil moisture levels and the presence of terminal sub-basins or "dead drainage areas" (Mowchenko and Meid 1983). A considerable rise in water level at potential outlets of those sub-basins would be required before outflow could reach the major basin. Consequently, the area weights assigned to each grid point cannot be assigned simply on the basis of percentage of land area. The approach being considered is to use ratios of "effective"/"gross" drainage areas. "Gross" refers to total land

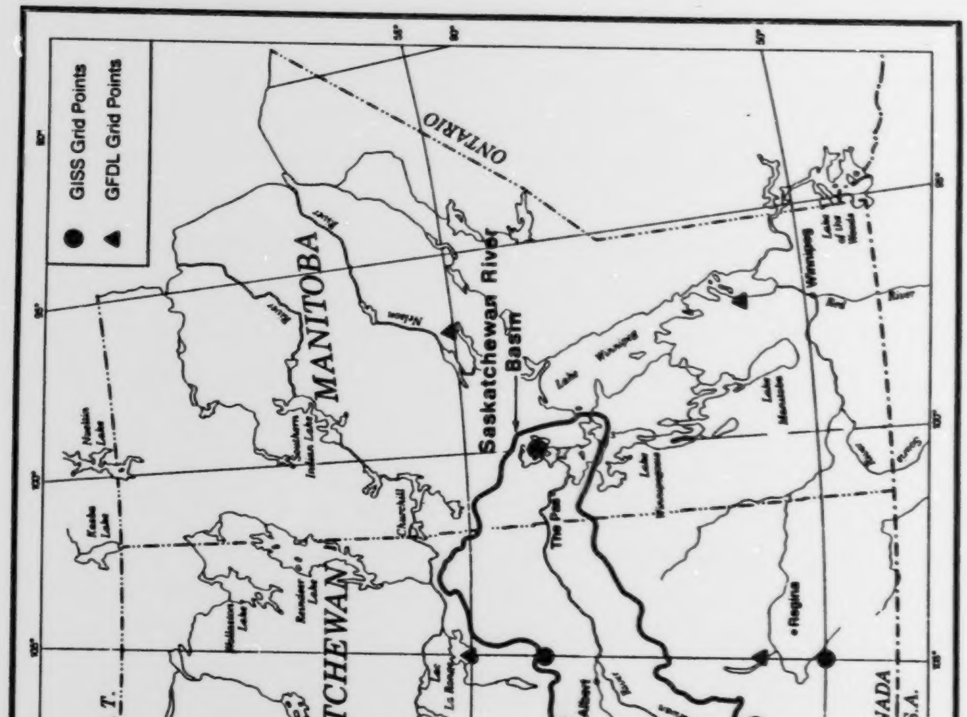
GISS Grid Points
GFDL Grid Points
N.W.T.
ONTARIO
MANITOBA
SASKATCHEWAN
ALBERTA
BRITISH COLUMBIA
CANADA
U.S.A.
Saskatchewan River Basin
Edmonton
Calgary
North Battleford
Saskatoon
Prince Albert
The Pas
Regina
Winnipeg
Lake Winnipeg
Lake Winnipegosis
Lake Manitoba
Lake of the Woods
Lac La Ronge
Cree Lake
Lake Athabasca
Lesser Slave Lake
Wollaston Lake
Reindeer Lake
Southern Indian Lake
Kasba Lake
Nueltin Lake
Churchill
Nelson River
Peace River
Red River

Figure 4. Saskatchewan River basin, with grid points.

area which might contribute runoff under extremely wet conditions. "Effective" (or "dry") represents the area that directly contributes runoff during a flood with a return period of two years. This area is defined primarily in terms of hydrologic factors rather than topography (Mowchenko and Meid 1983).

Mowchenko and Meid (1983) determined an effective drainage area of 223 907 $km^2$ for the entire basin, resulting in an effective/gross drainage area ratio of 0.64. However, different sections of the basin have different ratios, conceivably ranging form 0.00 to 1.00. It will, therefore, be necessary to determine effective/gross drainage area ratios for each climate scenario data point before total basin runoff is calculated.

## 6. CONCLUSION

A draft framework for a complete impacts study of the Great Lakes region is shown in **Figure** 5. Many interconnections among climate, hydrology, water resources, and various sectors of the regional economy are indicated. A similar framework could be drawn for the Saskatchewan River basin, or any other major watershed. It is important that these interconnections be kept in mind when establishing the scope of an impacts study. Is the objective to examine the hydrology of the basin or is it a broader water resources study? The Great Lakes and Saskatchewan River case studies are examples of the latter, in that they are oriented toward exploitable water. A number of hydrologic issues, such as changes in timing of peak runoff, have not been considered. However, Gleick (1986) used the Thornthwaite approach to address these issues in a basin in California, so ,it seems reasonable to propose that similar studies could be done for basins in western Canada. There are a wide range of other models that could be utilized, but as of mid-1986 there were few cases available (Beran 1986).

The study of possible impacts of climatic warming scenarios on water resources is still in its formative stage, but the field is gaining in interest (Askew 1987, Beran 1986, Gleick 1987). This review has concentrated on only a small part of this field; that is, a suggested methodology for applying climate scenario data. Two general points can be made. First, look for ways in which climate can be expressed as a variable element in hydrologic

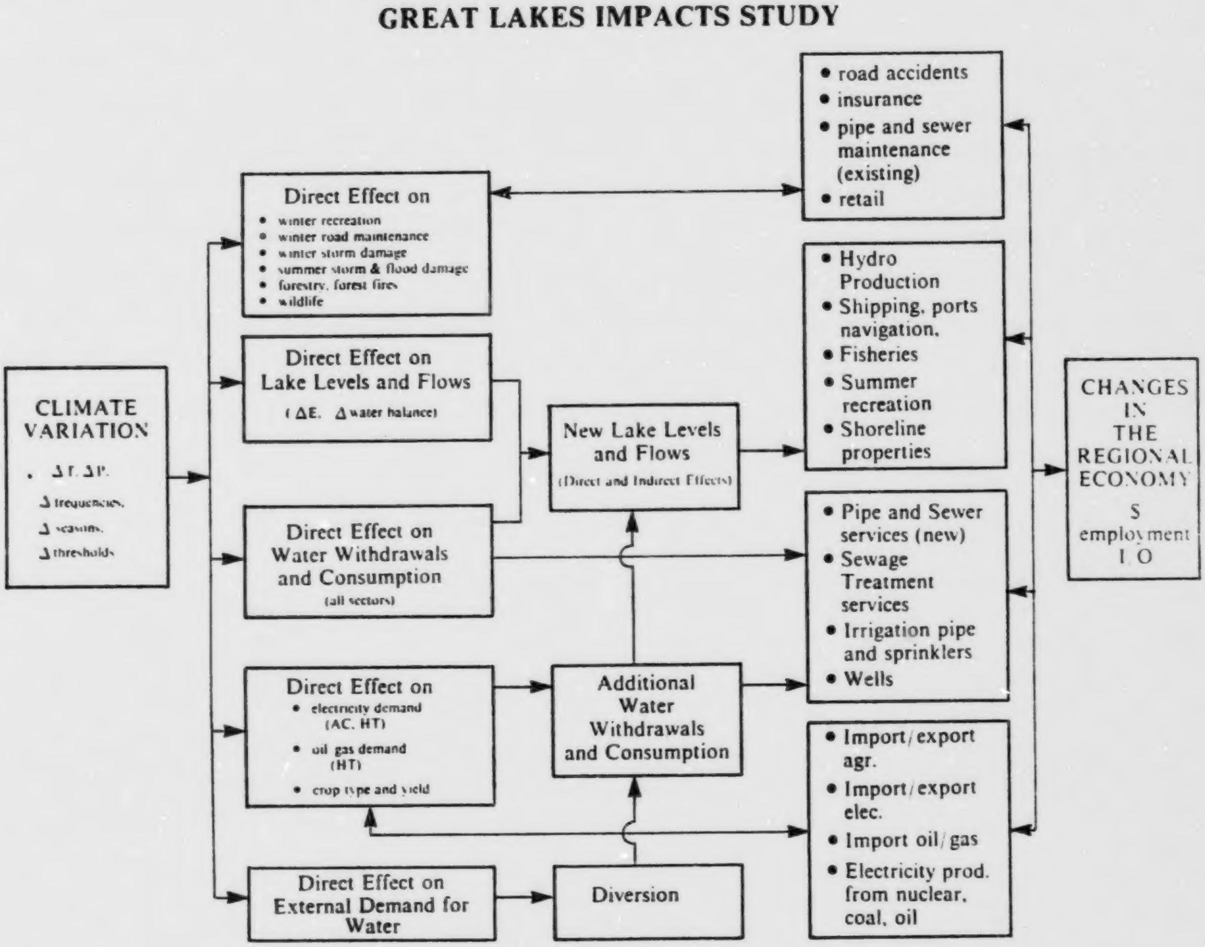
GREAT LAKES IMPACTS STUDY
CLIMATE VARIATION
Δ T, Δ P,
Δ frequencies,
Δ seasons,
Δ thresholds
Direct Effect on
winter recreation
winter road maintenance
winter storm damage
summer storm & flood damage
forestry, forest fires
wildlife
Direct Effect on Lake Levels and Flows
(ΔE, Δ water balance)
Direct Effect on Water Withdrawals and Consumption
(all sectors)
Direct Effect on
electricity demand (AC, HT)
oil gas demand (HT)
crop type and yield
Direct Effect on External Demand for Water
New Lake Levels and Flows
(Direct and Indirect Effects)
Additional Water Withdrawals and Consumption
Diversion
road accidents
insurance
pipe and sewer maintenance (existing)
retail
Hydro Production
Shipping, ports navigation,
Fisheries
Summer recreation
Shoreline properties
Pipe and Sewer services (new)
Sewage Treatment services
Irrigation pipe and sprinklers
Wells
Import/export agr.
Import/export elec.
Import oil/gas
Electricity prod. from nuclear, coal, oil
CHANGES IN THE REGIONAL ECONOMY
$
employment
I/O

Figure 5. Interconnected components of climate impacts and societal responses within the Great Lakes region. α = change, T = temperature, P = precipitation, E = evaporation, AC = air conditioning, HT = space heating, I/O = inputs/outputs (Cohen 1986a).

and water resources modelling. Second, consider the spatial and temporal resolution required for modelling, and apply interpolation techniques, where necessary, in order to overcome the "mismatch of scales" problem. This includes both the differences in resolution between global climate scenarios and regional climate, as well as the issue of instantaneous vs. gradual impacts that may be experienced by various elements in society and nature.

The methodology described herein can be used to provide "good" first-cut estimates at the regional scale, although it is obvious that a great deal of research into basic physical/hydrological processes is required before more definitive impacts studies can be pursued. It is hoped that this workshop will act as a catalyst for a broader long-term effort to investigate potential impacts of projected climatic warming on hydrology and water resources in western Canada.

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# SESSION II

## IMPACTS OF CLIMATE VARIABILITY/CHANGE ON THE PRAIRIE RESOURCE BASE

CHAIRPERSONS: E.G. O'Brien
Co-Chairman
Saskatchewan Climate Advisory Committee

J. Tokarchuk
Co-chairman
Manitoba Department of Agriculture

# KEYNOTE ADDRESS

# AN OVERVIEW OF CLIMATE IMPACT STUDIES

by

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University of Birmingham, England

## ABSTRACT

This presentation summarizes the alternative methods of analysis that have been developed for assessing the impact of climatic change. A wide range of effects are discussed, drawing examples largely from the agricultural sector. Substantial effects on crop yields may be expected, although these may vary significantly from region to region. As a result of this, some important changes may also occur in the regional pattern of crop potential and in the comparative advantage that some agricultural regions enjoy over others. A number of technological adjustments to mitigate the effects of climatic change are considered, including changes in crop variety, fertilizing and drainage, and land allocation.

## 1. INTRODUCTION

The purpose of this paper is to provide an introduction to recent studies in climate impact assessment. Consideration is first given to the types of climatic change that may affect agriculture and forestry. This is followed by discussion of the methods that have been developed, quite recently in most cases, to assess the effects of climatic change. There is then some consideration of the results of a few recent assessments, particularly of the potential effects of $CO_2$-induced climatic changes on agriculture and forestry. The paper concludes with an indication of the present gaps in our knowledge and our future research priorities.

## 2. TYPES OF CLIMATIC VARIATION

We can distinguish three types of climatic variation:

1. Short-term, frequent variation to which social and economic systems are generally adjusted.
2. Medium-term climatic variation to which society probably needs to adapt in order to avoid undesirable impact.
3. Long-term climatic changes that occur on time scales too large to be considered significant for the planning horizons of most societies.

This classification may seem somewhat unusual because it is based not on the nature of the climatic variations but, on their impact. It may be appropriate in this instance, however, since it is our task to assess impacts, not explain them. We may further pursue this line of argument by identifying two additional perspectives on climatic change. Once again, they are distinguished by their impact rather than by their nature. The first emphasizes the significance of gradual increases in mean surface temperatures likely to result from, for example, increases in atmospheric $CO_2$. These can be expected to lead to gradual, long-term, and cumulative changes in average regional climates. Following this view, we might conclude that, so long as we can predict the long-term climate trend, there need be no surprises in store for the farmer or forester. They should have time to modify their practices accordingly.

The alternative view emphasizes the changes in the frequencies of unusually disruptive (or beneficial) events that may result from changes in climate. This assumes that impact from climatic change comes not only from the average, but also from the extreme event. This point has been developed at some length elsewhere (Parry 1978, 1985). To illustrate, few farmers plan activities on their expectation of the average return. They gamble on good years and insure against bad ones (Edwards 1978). In general, we might expect subsistence farmers to tune their activities to bad years, attempting to minimize their impacts, while commercial farmers (such as those on the Canadian prairies) may tune their activities to good years. That is why the prairie farmer is periodically stressed when bad years prevail (McKay and Williams 1981).

Relatively small changes in mean climate can markedly alter the frequency of some short-term anomalies. For example, estimates from a recent study in Saskatchewan indicate that the frequency of drought could increase from 3% of all months to about 9% under a doubled $CO_2$ climate (Williams et al. 1987).

## 3. EFFECTS OF SOME RECENT CLIMATIC VARIATIONS

The view which emphasizes the importance of short-term anomalies is supported by the magnitude of impacts that has stemmed from recent, short-term variations of climate. The following examples serve to illustrate the array of potential impacts from possible climatic changes in the future, and types of response that have been adopted in the past.

### 3.1 THE EFFECT OF ISOLATED EXTREME EVENTS

### 3.1.1 Drought in the U.S. Corn Belt, August 1983

Midsummer 1983 saw a pronounced drought in the US corn belt and the southeastern United States. U.S. corn (maize) yields fell by nearly a third, from over 7000 kg/ha to about 5000 kg/ha (Figure 1). In the same year, however, as part of an effort by the United States Department of Agriculture (USDA) to reduce the national grain surplus, the Payment In Kind program (PIK)

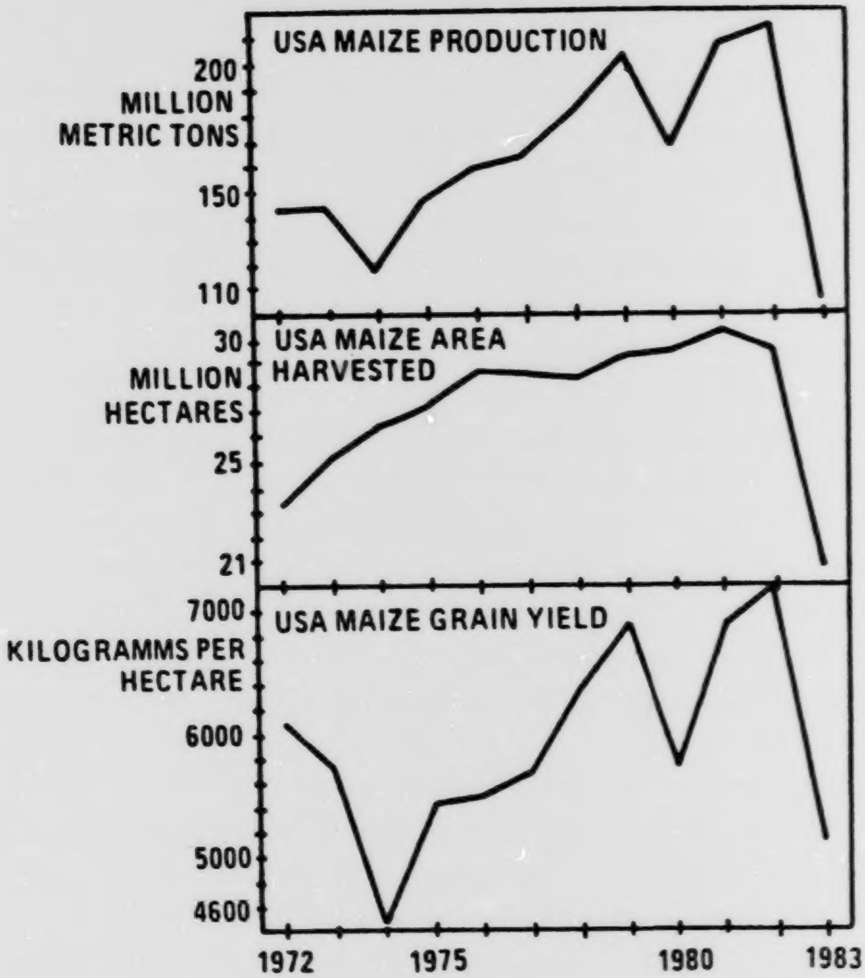


Figure 1. US maize production, area harvested, and grain yield, 1972 to 1983 (Parry and Carter 1986).

had encouraged large numbers of corn farmers not to plant. As a result, the US area planted to maize also fell by about a third, from 30 to 21 m ha (Figure 1). The combined effect of decreased yield and reduced area was a fall in US maize production by almost one half (from 210 mmt in 1982 to 110 mmt in 1983).

The effects were felt not only nationally, but also globally because US maize accounts for about one eighth of the world's total marketed cereal production. World total cereals production in 1983 fell by 3%; harvested area by 1.4%; and yield by 2%. These reductions were almost fully accounted for by the US figures alone (Figure 2).

### 3.1.2 Drought in the United Kingdom, 1976

From May 1975 to August 1976, rainfall in the south-east of England was about 60% of normal (Doornkamp et al. 1980). No drier spell of comparable length appears on the 300-year instrumental record. Almost all crops were affected. Nationally, potato yields were down 25% on the 1970 to 1974 average, and cereal yields dropped 10 to 15%. Since the planted area had not been substantially affected, falls in production were broadly commensurate; potato production was down 2.25 m tonnes and wheat down 2 m tonnes. The shortfall in cereal production required the import of around 1 m tonnes of cereal worth $80 million.

But prices responded accordingly. UK potato prices increased three-fold over 1975/76 and wheat a third over 1976/77 from the previous year. As a result, aggregate net income of the agricultural industry rose in real terms by 7% from 1975 to 1976, with little change from 1976 to 1977. Certainly, some farmers suffered, such as those engaged in livestock fattening in lowland areas where higher feed prices were not fully balanced by increased livestock prices. However, the general message of the 1976 drought is that market reactions, in combination with sensitive government response in raising guaranteed prices, can be an effective buffer against even the most severe of climatic events. The problem really arises when government policy is insensitive to climate. For example, the USDA's PIK program did not foresee that a massive drought-induced yield reduction, in combination with reduced

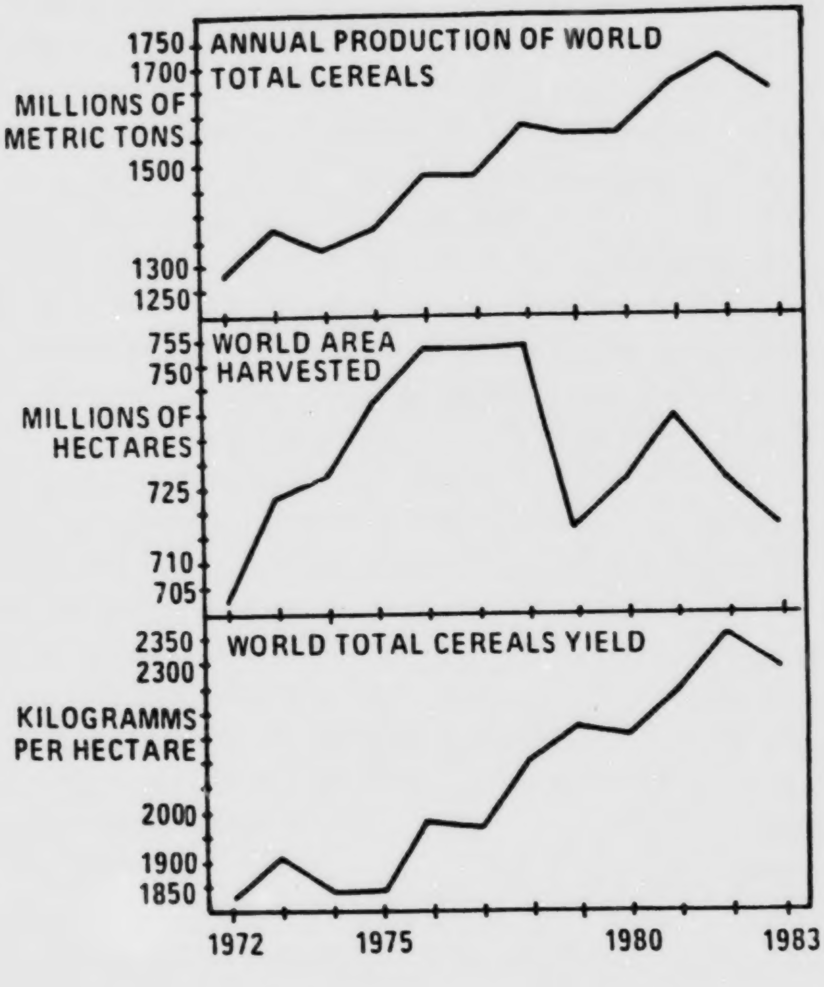


Figure 2. World total cereals production, harvested area, and grain yield, 1972 to 1983 (Parry and Carter 1986).

planting brought about by government policy, would lead to reductions in production that were almost twice as large as those intended. Fortunately, US maize yields were back up in the benevolent weather year of 1984. But if 1984 had also been a drought year, the outcome could well have been a severe drop in national and global cereal foodstocks. This leads us to consider the dramatic effects that a series of climatic anomalies can have on agriculture production.

### 3.2 THE EFFECT OF RECURRENT OR 'BACK-TO-BACK' CLIMATIC EVENTS

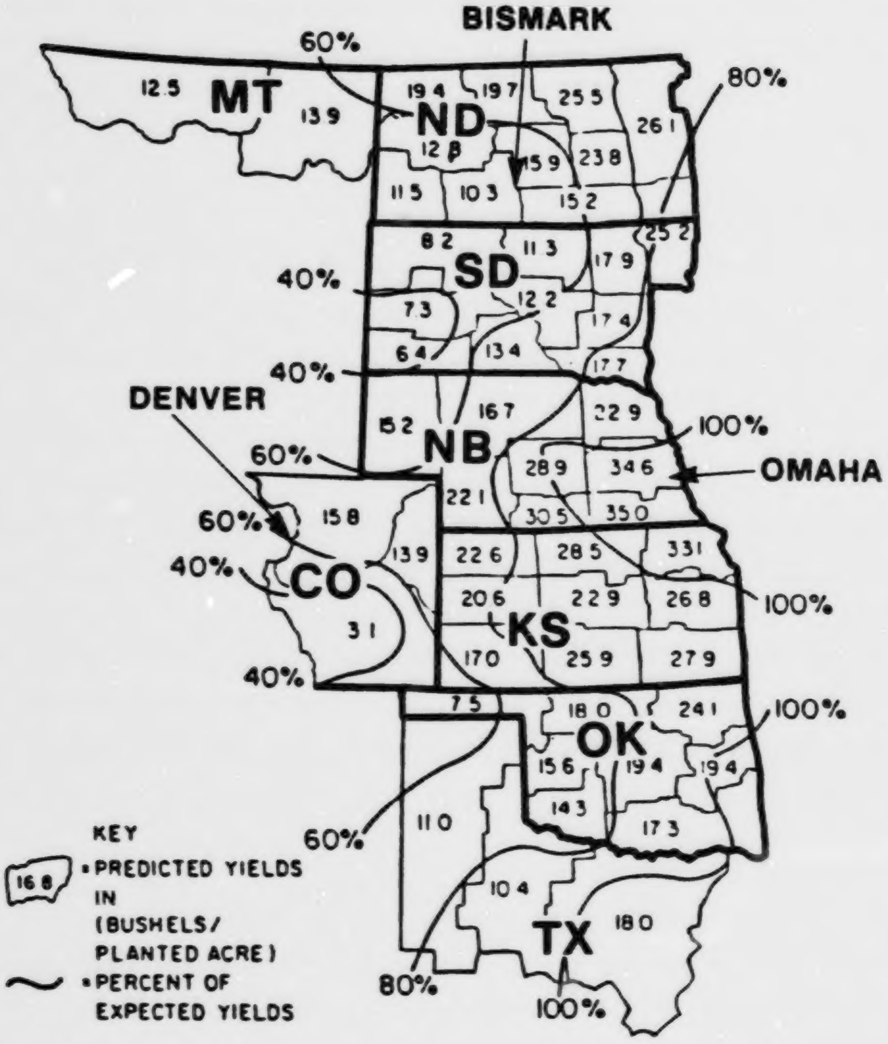
Runs or sequences of anomalous weather types tend to have a cumulative and compounding impact: the net effect being greater than the sum of the single extreme year effects. Over 1932 to 1937, for example, persistent drought in the US Great Plains helped bring about ca. 200 000 farm bankruptcies or involuntary transfers and the migration of more than 300 000 people from the region. If the same weather were to occur today, assuming 1975 technology and a 1976 crop area, the impact would still be considerable. For a recurrence of the worst weather year, 1936, simulated production shows a drop of 25%, reducing national wheat production by about 15% (assuming average production elsewhere in the US [**Figure 3**]). The cumulative effect could be substantial. Yearly yields, simulated for the weather over the period 1932 to 1940, would average about 9% to 14% below normal and amount to a cumulative loss over the decade equal to about a full year's production in the Great Plains (Warrick 1984).

## 4. ALTERNATIVE METHODS IN CLIMATE IMPACT ASSESSMENT

Over about the last 15 years, assessments of the effects of climatic changes have undergone a shift of emphasis from initial studies of impact to a growing emphasis on studies of interaction.

### 4.1 THE EMPHASIS ON IMPACTS

The impact approach is based upon the assumption of direct cause and effect, where a climatic event (e.g., a short-term variation of rainfall) operating on a given 'exposure unit' (e.g., a human activity) may have an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11 0
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10 4
TX
18 0
80%
100%
KEY
16 8
• PREDICTED YIELDS IN (BUSHELS/ PLANTED ACRE)
• PERCENT OF EXPECTED YIELDS

Figure 3. Simulated wheat yields on the Great Plains given 1936 weather and 1975 technology (Warrick 1984).

'impact' or effect [**Figure 4(a)**]. This approach to impact assessment frequently sought relatively simple statistical relationships between (for example) climate and agriculture, often as regression equations between weather and yield. They gave little attention to an understanding of the nature of the relationships.

## 4.2 THE EMPHASIS ON INTERACTIONS

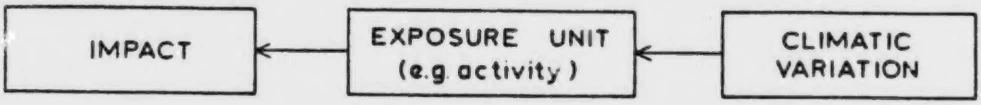
More recently, attention has been focussed on attaining a better understanding of the interactions between climate and human activity. This approach assumes that a climatic event is merely one of many processes (both societal and environmental) which may affect the exposure unit [**Figure 4(b)**]. To illustrate, it may be argued that the magnitude of the effect of the 1930s drought on the Canadian prairies was substantially increased by the depression of farm prices and the desperate economic straits that had been reached by many Prairie farmers before the drought began. In addition, widespread ploughing of soils prone to wind erosion increased the amount of windblown dust, which choked crops and reduced yields. Economics, weather, and farming technology thus interacted to create a severe economic and social impact that was perhaps pre-conditioned by the Depression, but was triggered by drought.

## 4.3 ORDERS OF INTERACTIONS

It is possible to achieve a greater realism in simulating the connection between climate and human activity by considering the 'cascade' of interactions that can occur from the first-order biophysical level, through second-order levels characterized by units of enterprise (farms, corporations, etc.), to third-order interactions at the regional and national level (**Figure 5**).

An appropriate example of this approach is the mixed hierarchy of simulation and regression models that was used in the Saskatchewan study (Williams et al. 1987). Altered levels of spring wheat yield (estimated using a simulation model for several climatic scenarios) were used as inputs to farm simulation models. They were converted to production figures and aggregated

a) Impact approach


IMPACT
EXPOSURE UNIT (e.g. activity)
CLIMATIC VARIATION

b) Interaction approach

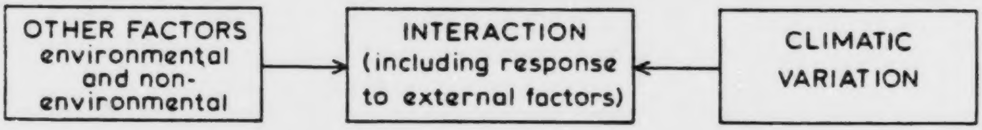

OTHER FACTORS environmental and non-environmental
INTERACTION (including response to external factors)
CLIMATIC VARIATION

Figure 4. Schema of simple (a) impact and (b) interaction approaches in climate impact assessment (Parry and Carter 1987).

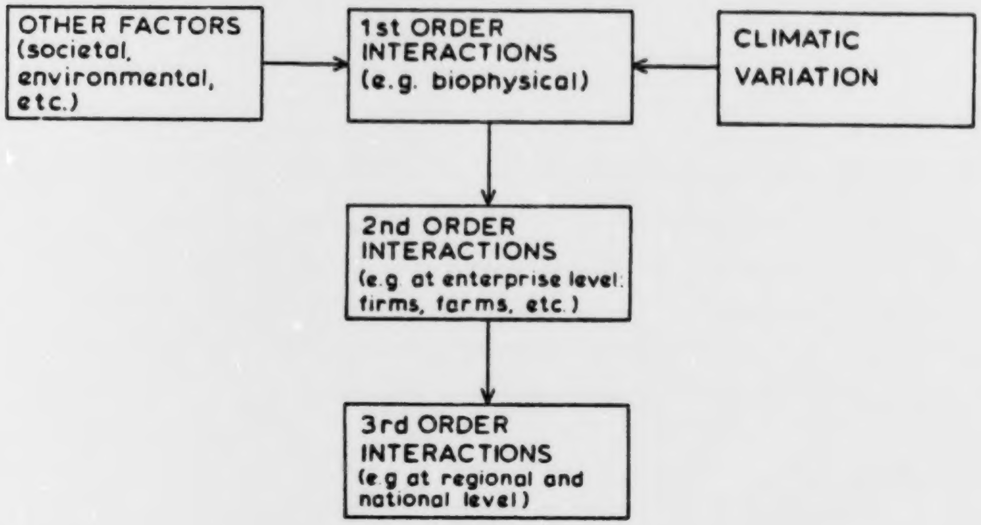

OTHER FACTORS (societal, environmental, etc.)
1st ORDER INTERACTIONS (e.g. biophysical)
CLIMATIC VARIATION
2nd ORDER INTERACTIONS (e.g. at enterprise level: firms, farms, etc.)
3rd ORDER INTERACTIONS (e.g at regional and national level)

Figure 5. Schema of climate interaction approach with ordered interactions (Parry and Carter 1987).

by soil zone and farm size to give provisional production and commodity changes. These were used, in turn, as inputs to a regional input-output model to examine impacts on both the agricultural and the non-agricultural sectors. A third (employment) model was used to translate changes in output for various economic sectors into changes in sectoral and provincial employment.

## 4.4 A FULLY-INTEGRATED APPROACH

Additional complexity can be introduced by studying interactions of the same order, both within individual sectors (such as between different farming systems) and between different sectors (such as between the concurrent effects of a climatic change on agriculture, forestry, water resources, etc.). The feedback effects operating between these sectors can also be examined (**Figure 6**). This form of fully integrated assessment has yet to be successfully implemented, largely because the full complement of systems models and our ability to connect them does not yet exist.

## 4.5 THE IIASA/UNEP PROJECT: A PARTIALLY INTEGRATED APPROACH

In a recent collection of 11 regional case studies of climate impact, funded by the International Institute for Applied Systems Analysis (IIASA) and the United Nations Environment Programme (UNEP), an attempt was made to link climate, biophysical, and economic models (Parry et al. 1987).

Scenarios, using outputs from climate models (e.g., atmospheric general circulation models) or data from instrumental climatic records, were used as inputs to agroclimatic models to predict potential yield responses to climatic change (**Figure 7**). To trace the downstream effects of yield changes, outputs from the agroclimatic models were used as inputs to economic models (farm simulations, regional input-output models, etc.). It was then possible to consider what policies might best mitigate certain impacts at specified points in the system.

The results of various studies that adopted these different approaches are summarized in the next section.

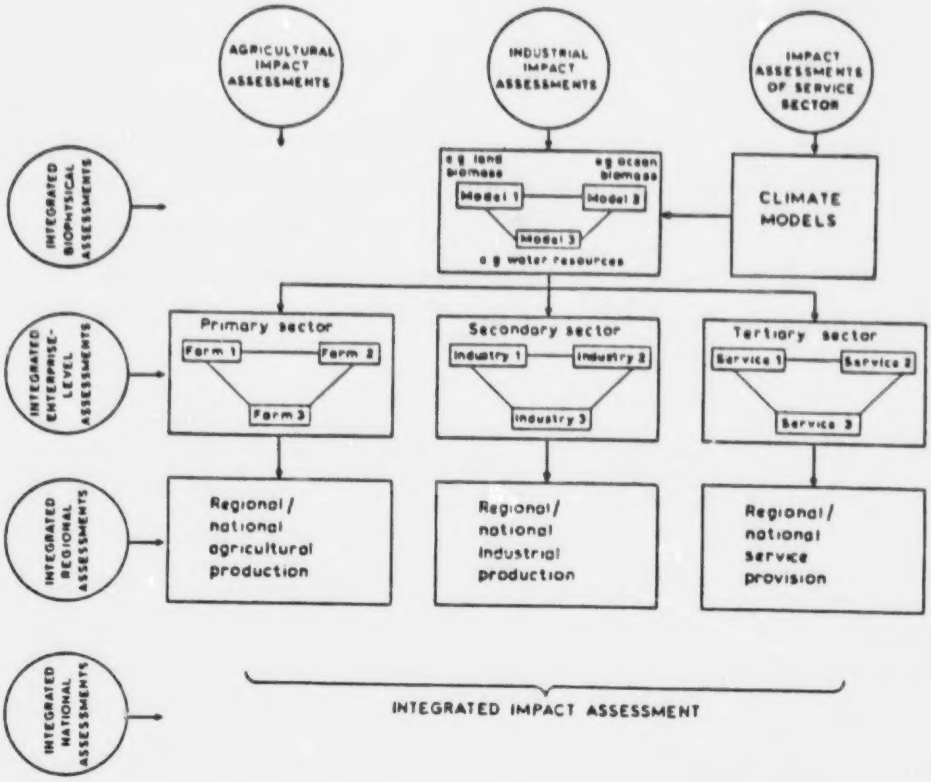

AGRICULTURAL IMPACT ASSESSMENTS
INDUSTRIAL IMPACT ASSESSMENTS
IMPACT ASSESSMENTS OF SERVICE SECTOR
INTEGRATED BIOPHYSICAL ASSESSMENTS
e g land biomass
e g ocean biomass
Model 1
Model 2
Model 3
e g water resources
CLIMATE MODELS
INTEGRATED ENTERPRISE-LEVEL ASSESSMENTS
Primary sector
Farm 1
Farm 2
Farm 3
Secondary sector
Industry 1
Industry 2
Industry 3
Tertiary sector
Service 1
Service 2
Service 3
INTEGRATED REGIONAL ASSESSMENTS
Regional/ national agricultural production
Regional/ national industrial production
Regional/ national service provision
INTEGRATED NATIONAL ASSESSMENTS
INTEGRATED IMPACT ASSESSMENT

Figure 6. A hierarchy of models for integrated impact assessment (Parry and Carter 1987).

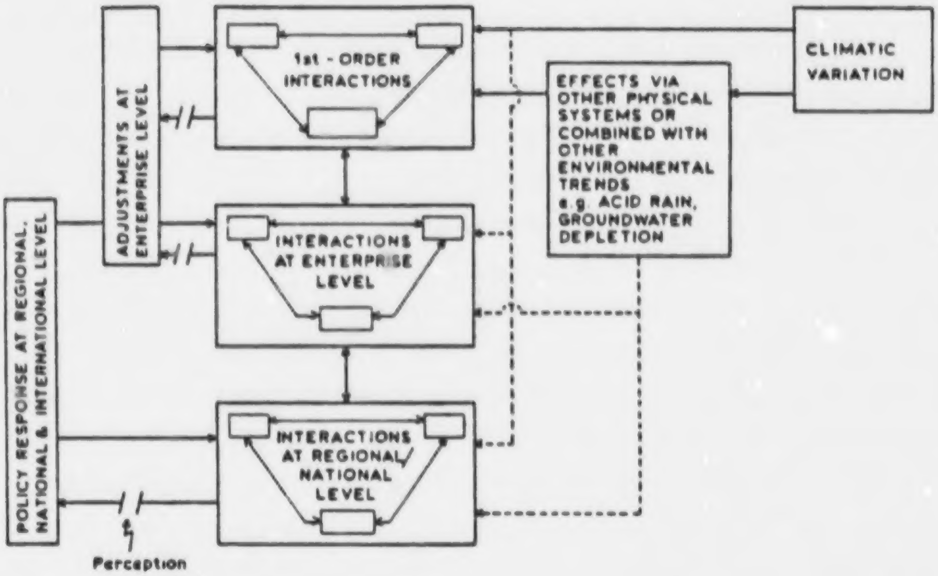

CLIMATIC VARIATION
1st - ORDER INTERACTIONS
EFFECTS VIA OTHER PHYSICAL SYSTEMS OR COMBINED WITH OTHER ENVIRONMENTAL TRENDS e.g. ACID RAIN, GROUNDWATER DEPLETION
ADJUSTMENTS AT ENTERPRISE LEVEL
INTERACTIONS AT ENTERPRISE LEVEL
POLICY RESPONSE AT REGIONAL, NATIONAL & INTERNATIONAL LEVEL
INTERACTIONS AT REGIONAL/ NATIONAL LEVEL
Perception

Figure 7. Schema of the IIASA/UNEP project's approach. This is an interactive approach with ordered interactions, interactions at each level, and some social and physical feedbacks (Parry et al. 1987).

## 5. SOME RECENT ASSESSMENTS

### 5.1 EFFECTS ON CROP YIELDS

A recent review of results from a number of studies (Warrick et al. 1986) suggests that, despite the diversity of modelling methods and scenarios adopted in different studies, there is a remarkable degree of unanimity regarding the expected direction of the effects of climatic changes on crop yields. Warming appears detrimental to cereals in the core wheat-growing areas of North America and Europe. With no change in precipitation or radiation, a slight warming (+1°C) might increase average yields by about 5 ± 4%, while a 2°C increase might reduce average yields by about 10 ± 7%. Reduced precipitation also tends to decrease yields, implying that both higher precipitation and higher temperature could have offsetting effects on yields.

To these conclusions, we should add that: (1) quite different effects on the same crop may occur in different regions, and (2) different cultivars may respond quite differently. We shall see later that these variations can be important in indicating the kinds of technological adjustments that may be most appropriate for responding to a given climatic change.

If, for the present, we ignore adjustments in agriculture, such as a switch of crops that is likely to accompany or at least follow a long-term climatic change, we may conclude that increased $CO_2$ concentrations will lead to decreases in yields in the order of 10% in the core wheat production areas of North America and the USSR. This prediction is based on the assumption that increased $CO_2$ and other greenhouse gases will cause warming to be enhanced in higher latitudes and summer dryness to become more frequent over the continents at middle latitudes in the Northern Hemisphere.

### 5.2 SPATIAL EFFECTS ON CROP LOCATION

One of the major adjustments most likely to occur is the spatial shift of cropping areas. This shift is somewhat akin to the shift of biomes that has occurred in response to long-term climatic changes in the past. To illustrate this, we may refer to the possible effects of climatic change on wheat- and maize-growing areas in North America. In Canada, an isopleth bounding the spring wheat-maturing zone can be related to photothermal timescale equations, which consider the date of first fall freeze, growing season temperature, and radiation conditions (Williams and Oakes 1978). For the US Corn Belt, the limits have been expressed in terms of minimum frost-free period for maturity, minimum and maximum thermal requirements, and moisture requirements (Newman 1980). Both crop zones are shown as shaded areas in **Figure 8**. In this example, an arbitrary decrease of $1^oC$ cooling with no change in precipitation would shift the belt in a southwesterly direction by about 175 km. Moisture stress would be reduced at the drier SW margin while the growing season would be reduced at the cool NE margin.

A logical development of this approach is to consider the shift in crop growing regions for climatic scenarios predicted by GCM 2 x $CO_2$ experiments. For example, for wheat in North America under the 2 x $CO_2$ climate derived from the Goddard Institute for Space Studies (GISS) model experiments, there occurs a large extension of the winter wheat belt into Canada, a switch from hard to soft wheat in the Pacific Northwest due to increased precipitation, and an expansion of areas in fall-sown spring wheat in the southern latitudes due to higher winter temperatures. In Mexico, wheat-growing regions remain the same, but greater high temperature stress may occur (**Figure 9**, Rosenzweig 1985).

### 5.3 POTENTIAL EFFECTS ON THE REGIONAL AGRICULTURAL ECONOMY

Hierarchies of linked models, similar to those discussed in Section 2, have been used in the IIASA/UNEP project to assess the potential effects of climatic changes on regional economies (Parry et al. 1987). While each set of models attempts to simulate a limited number of feedback effects within its own sub-system, the form of analysis is essentially sequential. This allows estimates to be made about a series of effects based on an assumed and essentially static set of agronomic and economic responses (Figure 7). These are "impact experiments" in the sense that they record the impacts that would occur if there were no changes in the farming system.

However, farming systems have been remarkably adaptive to climatic changes in the past and we can reasonably expect them to be as adaptive in the

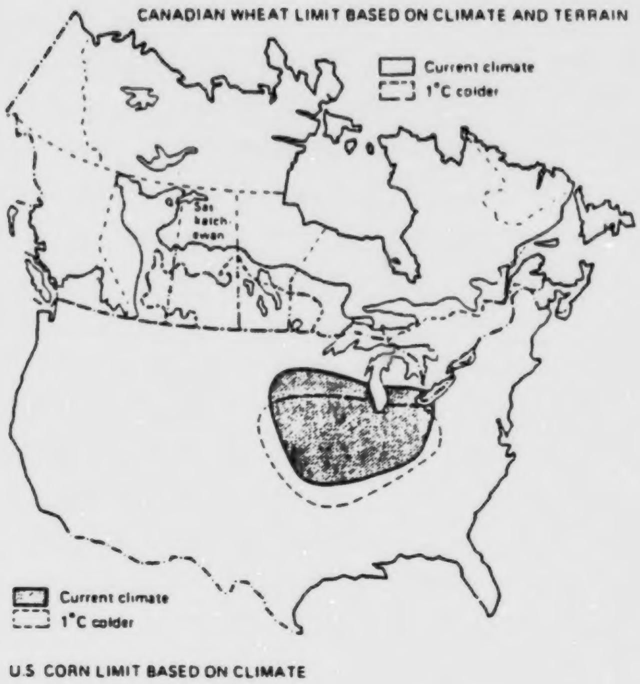

CANADIAN WHEAT LIMIT BASED ON CLIMATE AND TERRAIN
Current climate
1°C colder
Saskatchewan
Current climate
1°C colder
U.S CORN LIMIT BASED ON CLIMATE

Figure 8. Estimated shift of the Canadian Spring Wheat Belt and the US Corn Belt in response to a $1^{\circ}$C reduction in annual temperature (after Williams and Oakes 1978 and Newman 1980).

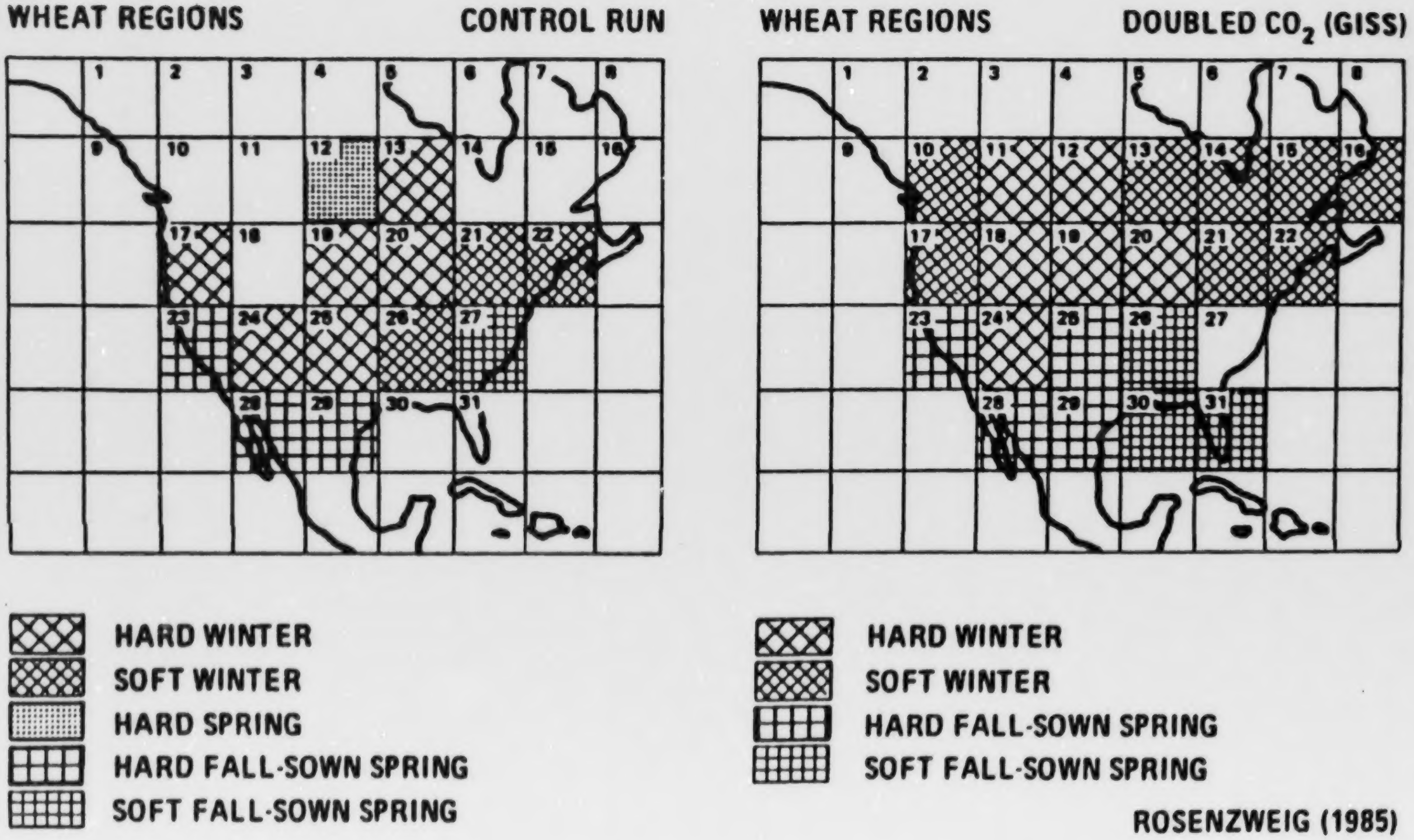

WHEAT REGIONS
CONTROL RUN
WHEAT REGIONS
DOUBLED CO2 (GISS)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
HARD WINTER
SOFT WINTER
HARD SPRING
HARD FALL-SOWN SPRING
SOFT FALL-SOWN SPRING
HARD WINTER
SOFT WINTER
HARD FALL-SOWN SPRING
SOFT FALL-SOWN SPRING
ROSENZWEIG (1985)

Figure 9. Simulated North American wheat-growing areas using (a) the GISS GCM control run and (b) the GISS GCM doubled $CO_2$ run (Rosenzweig 1985).

future. By altering some of the assumptions in our agroclimatic and economic models, it is possible to evaluate the various options that are available for either mitigating the negative effects of climatic change or exploiting the positive ones. We may experiment with a switch to a different crop, or to different amounts of fertilizer, or to different amounts of irrigation. For each set of these "adjustment experiments", we can generate a new set of impact estimates. These can be compared with the initial impact estimates, on the unadjusted system, and thus begin to identify the appropriate types of adjustment to various climatic changes.

In the summary that follows, we shall outline results selected from a wide range of experiments for both impacts and adjustments. Only a few experiments are presented here. These are drawn from studies conducted in Canada, the USSR., and Japan.[1] In each case study region, a series of three or four impact experiments was conducted along the lines outlined above and in a broadly compatible manner. These were then followed by a series of adjustment experiments to evaluate the appropriateness of various responses. In the examples summarized here, the emphasis was on the potential effects of climatic changes due to increased atmospheric $CO_2$. Scenarios of these changes were based on outputs from the 2 x $CO_2$ experiment for the GISS GCM. In order to compare these effects with the effects of short-term climatic variations, the results were compared with those for an extreme decade and extreme year scenario. Because different crop weather models require different data (10-day, monthly, annual, etc.), this array of scenarios varied somewhat among the case studies. The USSR study, for example, includes synthetic scenarios that vary temperature and precipitation by arbitrary increments. In general, however, the results permit comparison both of the potential effects of a 2 x $CO_2$ climate between different regions and of the effects of a long-term climatic change with the effects of short-term climatic variability. The results are, of course, not predictions. A high level of uncertainty is attached both to GCM predictions of regional climatic change and to the estimations of their effects on agriculture.

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[1] Other studies in the IIASA/UNEP project were conducted in Iceland, Finland, Ecuador, Brazil, Kenya, India, and Australia (Parry et al. 1987).

## 5.4 REGIONAL VARIATIONS IN EFFECTS ON CROP YIELDS

As indicated above, the higher temperatures which may be expected under conditions of increased atmospheric $CO_2$ tend to favour higher yields of cereal crops in regions where temperatures now limit the growing season. To illustrate, if we assume that these warmer conditions do not create problems in water supply and that, for example, Japanese rice production will remain fully irrigated, we may expect average rice yields in central Japan (Tohoku) to increase by perhaps 5% (Yoshino et al. 1987). Where, however, cereal production is already drought prone, increased rates of evapotranspiration may well place a break on output. Saskatchewan simulations of wheat yield point to severe early summer moisture stress on young spring-sown wheat plants, with consequent yield reductions of between one fifth and one third.

One way of mitigating these negative effects is to switch from spring to winter-sown wheat. However, the regional pattern of crop yield responses can be expected to be extremely varied for a number of reasons.

### 5.4.1 Spatial Complexity of the Climatic Change

This is not simply the result of the varying degrees of absolute change in climate in different regions, but also stems from the ratio of this change to the existing climate. Thus, while effective temperature sums (ETS) in central Japan (Tohoku) increase by 27% in the GISS 2 x $CO_2$ experiment, in the north at Hokkaido (where they are already one quarter lower than in the centre), the increase is 37%. Thus, much of the variation in yield responses estimated for irrigated rice in Japan is a function of the geography of existing agroclimatic potential.

### 5.4.2 Spatial Complexity Introduced by Non-climatic Factors

In the estimates presented above, we have assumed the same terrain, soils, management, etc. When regional variations are introduced, quite localized responses to climatic change can result. Overlain on these variations are differences in infrastructure (farm size, etc.) and management (levels of fertilizer application, pesticides, etc.). Even if we assume the same management for all farm sizes, the effects of similar yield changes on farm income vary according to farm size partly because of varying yield-income functions and partly because different-sized farms are found on different soil types.

### 5.4.3 Differential Crop Responses

Since different crops have different growing requirements, they frequently respond quite differently to changes in their environment. In the central European USSR, for example, a moderate warming would increase winter wheat yields (which are at present limited by a short, relatively cool growing season) but decrease barley yields (since spring-sown barley is suited to cool conditions but is susceptible to the early summer moisture stress that might accompany increased temperatures) (Pitovranov et al. 1987).

## 5.5 RESULTANT CHANGES IN CROPPED AREA

Two consequences flow from the geographic complexity described above; there are spatial shifts of crop potential and spatial shifts of comparative advantage.

### 5.5.1 Spatial Shifts of Crop Potential

New locations will be defined for areas which, under present climatic conditions, are judged to be most suited to a given crop, combination of crops, or specified level of management. In essence, a change in the range of crops that can be profitably grown at a particular place will occur. This is a result of the shift of the physiological limits for growth of different crops. For example, under a warmer climate, both winter and spring wheat might expand northwards, assuming that terrain and soils permit. This is well illustrated in northern Japan where the limits of the "safely cultivable" area for irrigated rice fluctuate quite markedly between warm and cool periods, and could be expected to expand under a climatic warming induced by increased atmospheric $CO_2$ or other greenhouse gases (Figure 10).

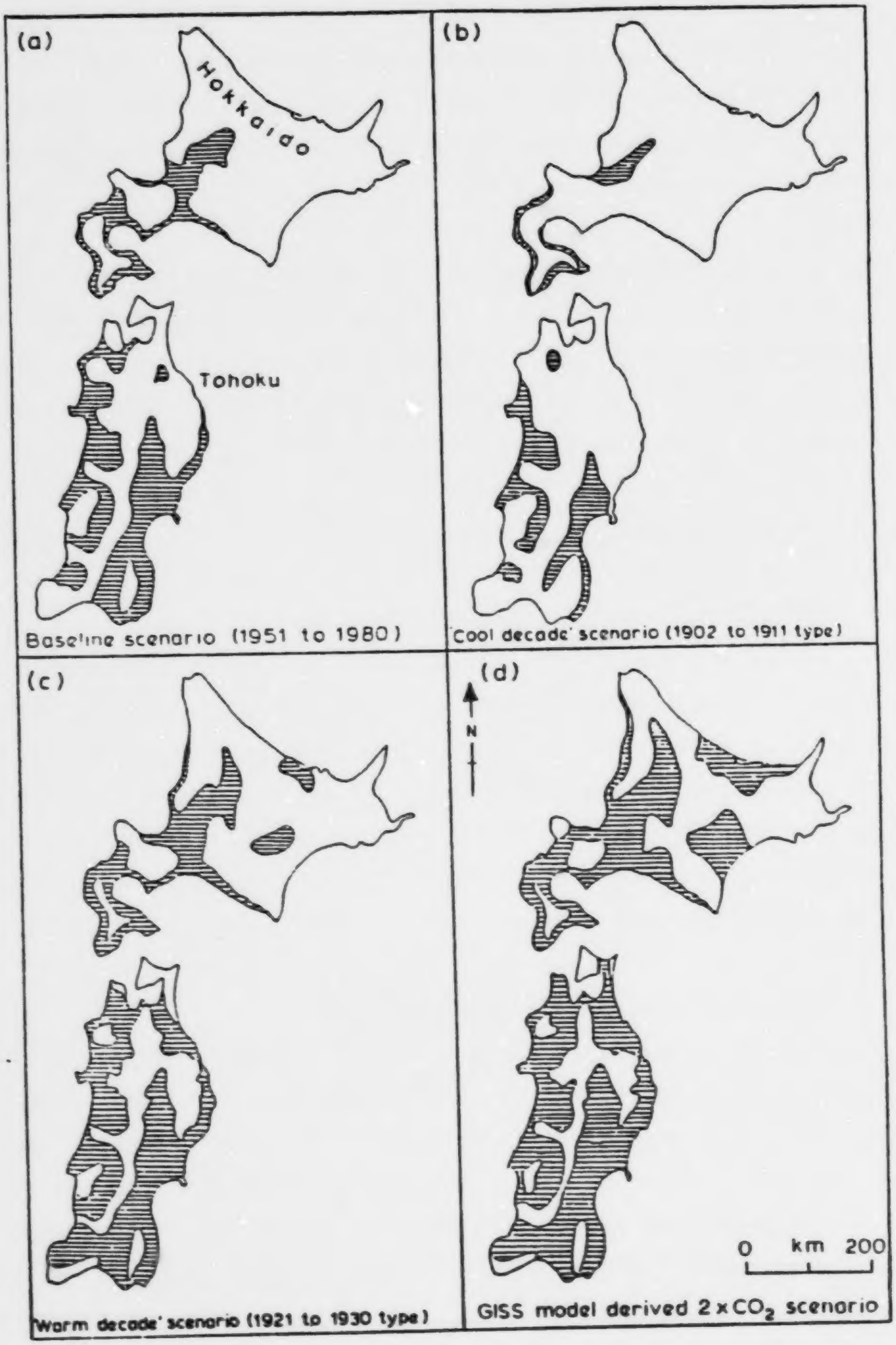

(a)
Hokkaido
Tohoku
Baseline scenario (1951 to 1980)
(b)
'Cool decade' scenario (1902 to 1911 type)
(c)
'Warm decade' scenario (1921 to 1930 type)
(d)
N
0 km 200
GISS model derived 2 x CO2 scenario

Figure 10. Shift of safely cultivable area for irrigated rice in Hokkaido, North Japan (Yoshino et al. 1987).

### 5.5.2 Spatial Shifts of Comparative Advantage

Much more important are likely to be the changes in area under different crops resulting from differential changes in yield. In turn, this will result in changes either in the relative profitability at a particular place or in the comparative advantage that one crop may hold over another (for details see Parry and Carter 1987).

### 5.5.3 Inter-regional Differences in Crop Yield Sensitivity

The picture is further complicated by the fact that the same crop grown in different regions will respond differently to the same change in climate. In northern Finland, under a 2 x $CO_2$ GISS climate, for example, barley would do well with a higher ETS without a moisture shortage, whereas in southern Finland, yields could actually decrease due to early summer moisture stress (for details see Kettunen et al. 1987).

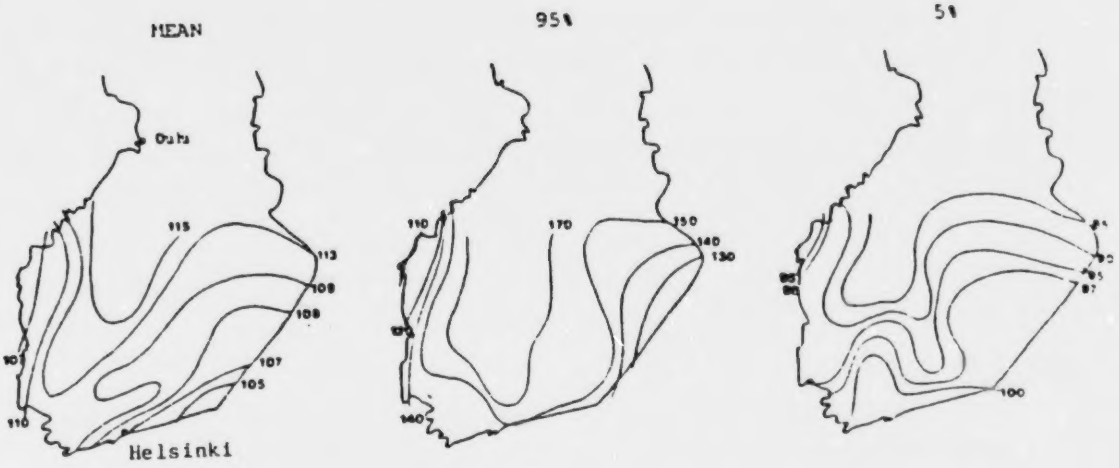
## 5.6 EFFECTS ON CROP RESPONSES TO MANAGEMENT

One of the difficulties in estimating effects of climatic change on agriculture is that the sensitivity of yield to inputs such as fertilizers and pesticides also varies with climate. Generally speaking, the closer the climatic conditions are to ideals for plant growth, the greater is the plant response to fertilizer applications. This means that adjusting levels of fertilization can be an effective means of stabilizing yield variability resulting from short-term climatic changes (see below).

## 5.7 EFFECTS ON VARIABILITY OF PRODUCTION

Even if we disregard changes in inter-annual variability of temperature and rainfall which may occur with a transition to a warmer climate, and assume that climatic variability remains unchanged, the effect of a change in mean climate on mean yield can be different from its effect on above- or below-average yields. Figure 11, for example, shows that in central and southern Finland quite different changes occur in the lowest (95 percentile), mean, and highest (5 percentile) spring wheat yields simulated for recent cool (1974 to 1982) and warm (1966 to 1973) periods.

a) Warm period (1966-73) scenario


MEAN
95%
5%
Oulu
115
113
108
108
107
105
107
110
Helsinki
110
170
150
140
130
170
140
100
97

b) GISS 2 x $CO_2$ scenario

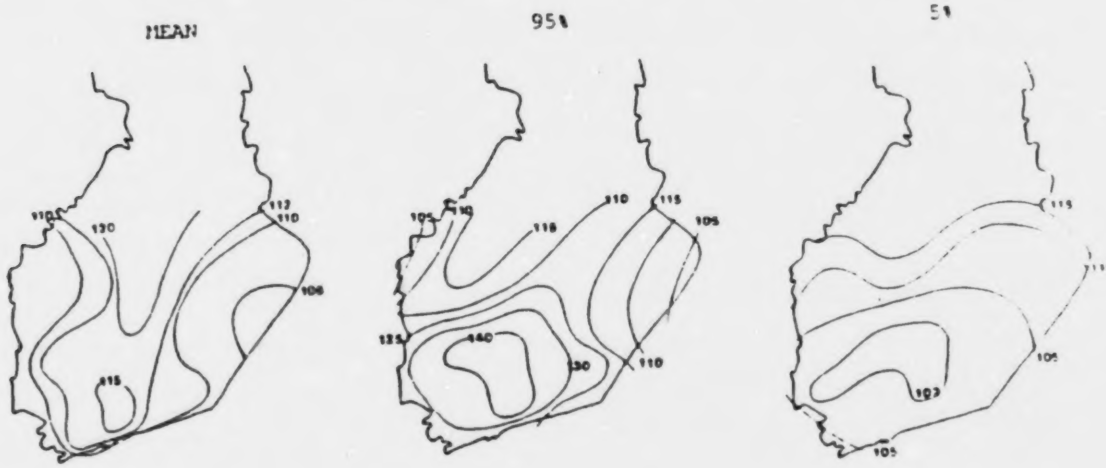

MEAN
95%
5%
110
120
112
110
106
115
105
110
115
110
115
105
125
140
130
110
115
105
103
105

Figure 11. Effect of climate on mean, lowest (95 percentile), and highest (5 percentile) spring wheat yields in Finland for (a) warm period 1974 to 1982, with present-day variety; (b) GISS 2 x $CO_2$ climate with adapted variety having thermal requirements 120 growing degree days (GDD) greater than present varieties. Isolines indicate percentage of yield simulated for the period 1959 to 1983 (Kettunen et al. 1987).

Similar (though perhaps less pronounced) differences are likely to occur with different wheat varieties under a GISS 2 x $CO_2$ climate.

## 5.8 DOWNSTREAM ECONOMIC EFFECTS

From experiments with farm simulation models and input-output models, we can estimate the effects of climatic changes, via crop yields, on farm incomes, employment, and levels of economic activity in non-agricultural sectors. These allow an estimation of the effects of a specific climatic event, such as an extreme dry year or dry decade, if that event were to occur now. But these background factors are constantly changing and, indeed, would almost certainly change in response to a longer-term transient change in climate resulting from, for example, increases in atmospheric $CO_2$ or other greenhouses gases.

With these caveats in mind, experiments in Saskatchewan indicate that, under the changes in temperature and precipitation indicated by the GISS 2 x $CO_2$ experiment, total provincial farm income decreases by 26%; on-farm employment by 3%; and provincial gross domestic product by 12%.[2] In this experiment, the change in climate is treated as a sudden, step-like event in which no adjustment is allowed for changes in technology, management, prices, harvested area, etc. In reality, we can be sure that these would change substantially between now and the time at which levels of atmospheric $CO_2$ are doubled.[3]

## 5.9 SOME TECHNOLOGICAL RESPONSES TO CLIMATIC CHANGES

In this section, we refer only to adjustments that could be put in place now, since this enables us to parameterize and input them to the linked models. Vague assumptions about future changes in technology, demand, and prices are much less easy to specify. The adjustments are of four types: crop variety, soil management, land allocation, and purchases to supplement production.

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[2] Considerable margins of error embrace these estimates. For details, see Williams et al. (1987).

[3] Current estimates for the $CO_2$ doubling time lie between 2050 and 2100 A.D.: Bolin et al. (1986).

## 5.10 CHANGES IN CROP VARIETY

### 5.10.1 Changes from Spring to Winter Varieties

Our investigations in Canada, Finland, and northern USSR indicated that some spring-sown crops (e.g., wheat, barley, and oats) experienced reduced yields under the GISS 2 x $CO_2$ climate due to the increased frequency of moisture stress early in the growing period. A switch to winter wheat, or in some areas winter rye, might reduce the effects of high evapotranspiration in the early summer as well as take advantage of the longer potential growing season. This assumes that snow cover is sufficient to protect the crop against winter kill.

### 5.10.2 Change to Varieties with Higher Thermal Requirements

A logical way of exploiting longer and warmer growing seasons at high latitudes is to use later maturing varieties with higher thermal requirements. In some cases, the yields of present-day varieties such as spring wheat in northern USSR tend to be reduced under the GISS 2 x $CO_2$ climate. However, spring wheat varieties with thermal requirements 50 or 100 growing degree days (GDD) greater than present-day varieties exhibit increased yields.

### 5.10.3 Change to Varieties Giving Less Variable Yields

We know little about what changes could occur in the inter-annual variability of temperature and precipitation. But, even if we assume the same degree of variability under an altered climate, the effects on crop yields are not insignificant and it is possible to test a number of varieties for stability of yield. Figure 12 graphically illustrates the effects of the GISS 2 x $CO_2$ climate on two different varieties of rice (for further details see Yoshino et al. 1987).

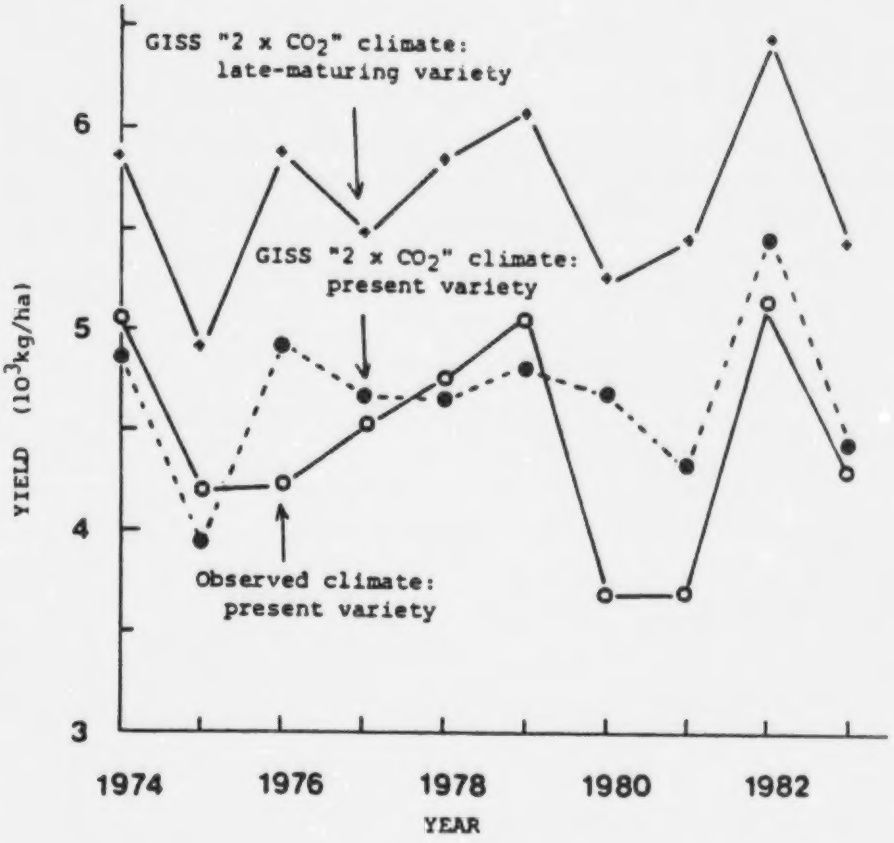

Figure 12. Simulated rice yield under present (observed) and GISS 2 x $CO_2$ climate applied to 1974 to 1983 in Hokkaido, North Japan. Responses to doubled $CO_2$ climate for two varieties of rice are shown (Yoshino et al. 1987).

## 5.11 CHANGES IN FERTILIZING AND DRAINAGE

### 5.11.1 Altered Fertilizer Applications

The IIASA/UNEP project includes two types of fertilizer experiment. The first increases levels of fertilizer application to optimize yields under a GISS 2 x $CO_2$ climate. The second varies applications in order to maintain, for example, 1980 production levels. Variable applications of fertilizer to stabilize yields by offsetting the effects of anomalously cool or warm summers are presently being tested for feasibility by the Icelandic government (for details see Bergthorsson et al. 1987).

### 5.11.2 Improvements in Soil Drainage

Increased precipitation predicted in the GISS 2 x $CO_2$ experiment might be expected to lead to increased soil erosion. This might offset the beneficial effects of warmer climates and technological improvements. Improvements in soil drainage are, therefore, an adjustment which is tested by the IIASA study in the Leningrad region, northern USSR. The impact indicated is of slightly reduced winter rye yields, presumably as a result of the leaching of soil nutrients. This effect would have to be weighed against reduced erosion and more efficient disposal of nitrate pollutants in the region, in order to assess fully the consequences of such a measure (Pitovranov et al. 1987).

## 5.12 CHANGES TO LAND ALLOCATION

### 5.12.1 Changes of Land Use to Optimize Production

Various crops respond differently to changes in climate and levels of fertilizer application under those climates. Therefore, any attempt to maximize output of each crop while minimizing production costs is likely to identify quite different allocations of land to alternative crops under different climates. In the Central Region, European USSR, experiments for a 1$^{\circ}$C arbitrary increase in the mean annual temperature indicate an "optimal" land use which increases the area under winter wheat, corn, and vegetables, while decreasing the allocation to spring-sown barley, oats, and potatoes (see above). This pattern of land use resembles that presently found further south in the USSR and points to the value of using regional analogues to identify possible responses to climatic change. We shall return to this point later.

### 5.12.2 Changes of Land Use to Stabilize Production

Experiments by the Prairie Farm Rehabilitation Administration (PFRA) in Saskatchewan have tested the efficacy of removing marginal cropland from production as a means of drought mitigation. The present work has identified previously unimproved land brought into wheat production over 1951 to 1981. This amounts to about 14% of all present cropland. Wheat crops on this land tend to be profitable in years of normal or above-normal rainfall, but can result in major losses in dry years. In the experiments, this land is "converted back" from wheat to pasture for beef cattle. Total provincial output from the new mix of land uses is compared with that from the present land use for a variety of drought and non-drought years (Fautley, personal communication 1986).

## 6. EFFECTS ON FOREST ECOSYSTEMS AND TIMBER PRODUCTION

A spatial shift of climatic zones resulting from a change of climate would lead to a spatial shift of vegetation types. But the rate of response would depend on the migration rates of the species. These vary greatly between various taxa; between 10 and 100 m per year for many cool temperate forest species in Europe (Shugart et al. 1986). There is evidence that considerable changes in the distribution of forests have occurred as a result of climatic changes in the past. For example, the transformation from spruce-dominated to jack pine-dominated forests in eastern Minnesota, ca. 10 000 years ago, occurred over a few hundred years at most, and perhaps in less than one hundred (Shugart et al. 1986). More recently, we may note the effect of even a small fluctuation, such as the series of warm summers in northern Scandinavia in the 1930s, leading to regeneration of the boreal forest at its northern limit and a measurable advance of the timber line (Shugart et al. 1986). If we ignore our uncertainties about the rates of climatic change that might occur as a result of increasing atmospheric $CO_2$ and the rates of migration of forest species in response to an altered climate, we can consider the equilibrium locations of forests that might be expected for a given scenario of climatic conditions. Emanuel et al. (1985) have mapped the changes in vegetation, as classified by Holdridge Lifezones, that would result from altered temperature and precipitation values available from the Manabe and Stouffer (1980) climatic change scenario.[4] Comparison of the base climate and 2 x $CO_2$ maps shows a 37% decrease in the areal extent of the boreal forest. It is replaced at its southern edge by cool temperate steppe and, to a lesser degree, by cool boreal forest.

More insight into how forests might respond to climatic changes can probably be achieved by running computer simulations of forest growth, appropriately validated against independent data. An example of this is an experiment by Solomon and Shugart (1984) using the FORET model for 72 species of trees in eastern North America. The simulations were initiated on a bare plot and allowed to run for 400 years under a stable present-day climate. After a simulated 400 years, averages of temperature and precipitation were altered to represent a 2 x $CO_2$ climate. Between a simulated 500 and 700 years, they were altered by linear interpolation from a 2 x $CO_2$ to a 4 x $CO_2$ climate. The general results of the study have been summarized by Shugart et al. (1986) as follows:

1. A dieback of many dominant trees occurred, particularly in the transition between boreal and deciduous forests.
2. Temperate deciduous trees invaded the southern boreal forest but were delayed by the presence of the boreal species.
3. There was a shift in overall forest vegetation that resembles the pattern obtained from the Holdridge experiments by Emanual et al. (1985), with a time lag of up to 300 years.

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[4] Values from the Manabe and Stouffer experiment, which was for 4 x $CO_2$, were halved to approximate the 2 x $CO_2$ values.

Some preliminary studies have recently been undertaken to consider the economic implications of these large-scale spatial shifts of forest types. As in the case of assessing economic impacts in agriculture, the task is one of using outputs from the GISS GCM 2 x $CO_2$ experiment with a simple growth model; then using the estimates of changes in growth and forest area as inputs to an economic model. In the first part of the study, Kauppi and Posch (in Parry et al. 1987) correlated the location of the boreal forest with minimum and maximum effective temperature sum (ETS) requirements. They remapped the ETS boundaries for the 2 x $CO_2$ climate and inferred the northward displacement of the boreal forest (Figure 13). From these maps, Binkley (in Parry et al. 1987) has calculated, country by country, (1) the change in productive area, as taiga areas become warm enough to support forest ecosystems, and (2) the increase in growth on extant forest lands. Using these new data, the IIASA global forest sector model[5] was solved for a 50-year projection horizon to provide estimates of changes in price, harvest, and income from timber sales. In general, timber producers in northern regions benefit by the warmed climate, although the size of the benefit is small, except in Finland. Income from timber sales declines for all producing countries, except Finland and Canada, as a result of a substantial price fall. Full details are reported in Binkley (in Parry et al. 1987).

## 7. RESEARCH PRIORITIES

Four main needs for future research emerge from this summary. First, we require more specific and user-oriented information regarding climatic change: its likelihood, nature, magnitude, areal extent, duration, and most important, rate of onset. It is also important that information on variability be available so that we have estimates of possible changes in extreme conditions which are important in agricultural decision making.

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[5] This model projects production, consumption, prices, and trade of 16 forest products in 18 countries on the basis of forest growth, timber supply, processing facilities, and final demand.

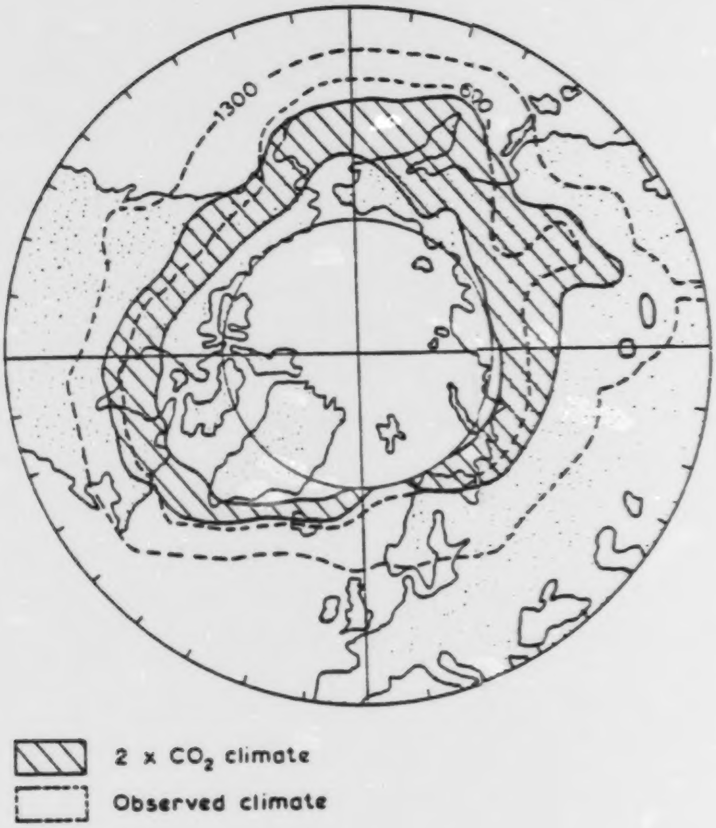
1300
600
2 x CO₂ climate
Observed climate

Figure 13. Hypothetical shift of the boreal forest zone for the GISS $2 \times CO_2$ climate scenario. The zone is delimited between effective temperature sum isopleths of 600 and 1300 degree-days [Kauppi and Posch. In: Parry et al. (eds.) 1987].

Second, an important path of climatic impact on the most climate-sensitive sectors of our society (farming, fishing, and forestry) is an *indirect* one; that is, it is based on changes in other physical systems, such as soil chemistry, agricultural pests and diseases, and their vectors. Although we have barely begun to grasp these interactions, they clearly have a major influence on some production systems.

Third, we need to specify with greater precision the interaction between climate and other resources in the primary sector, by modelling (empirically or by simulation) crop/climate and timber/climate relationships. It should then be possible to trace, with greater confidence, the downstream effects of these first-order impacts on other sectors of the economy and society. This will be accomplished by reference to a hierarchy of the three types of models we have considered: climatic, impact, and economic.

Finally, and perhaps most important, we need to explore in greater detail the range of technological and policy adjustments available in agriculture. We need to evaluate their efficacy in mitigating negative impacts or exploiting new options offered by changes of climate.

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# ESTIMATING EFFECTS OF CLIMATIC VARIABILITY AND CHANGE ON PRAIRIE AGRICULTURE IN CANADA

by

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## ABSTRACT

This study of climatic variability in Saskatchewan is one of five international case studies sponsored by the International Institute for Applied Systems Analysis/United Nations Environment Program (IIASA/UNEP). These studies investigated the impacts of climatic change and variability on food production in cool temperate and cold regions. The case studies are linked by investigations of the potential impacts on agriculture of a common set of climatic scenarios; two which are historically based and one that is based on a doubling of $CO_2$ concentration. Historical scenarios for each study were selected on the basis of a 1-year and a 5- to 10-year period that were particularly important in terms of their climatic impact on agriculture.

Scenarios used in the Saskatchewan study include the single year (1961), the 5 to 10-year period (1929 to 1938), and the General Circulation Moodel (GCM) results derived for a doubling of atmospheric $CO_2$ by the Goddard Institute for Space Studies (GISS). Results of the historical analysis suggest that, in an extreme drought year, Saskatchewan can expect moisture resources so reduced that wind erosion potential is doubled and spring wheat production reduced to about 25% of normal, resulting in direct losses to the agricultural economy of more than $1.8 billion (in 1980 dollars) and 8000 jobs, and a further reduction in other sectors of the economy of $1.6 billion and 17 000 jobs. For an occasional extreme 5- to 10-year drought period, dry matter production in Saskatchewan could be reduced by nearly half and spring wheat production by about one-fifth. This would result in direct agricultural losses of about $0.6 billion and 2600 jobs; and a reduction in other sectors of the provincial gross domestic product (GDP) of more than $0.5 billion and 5600 jobs.

Based on a shift to a warmer and moister climate, as projected by the GISS-GCM experiments, wind erosion potential in Saskatchewan could be reduced

and potential biomass productivity increased. However, with droughts becoming more frequent and severe, and without major adaptive changes by agriculture, a long-term reduction in spring wheat production of about 16% could be expected. Subsequent losses to agriculture would average over $160 million and 700 jobs annually. A long-term shift to a warmer climate, without precipitation increases, would generally cause all impacts to be adverse and more intense, particularly as a consequence of increased drought frequency and severity. Findings suggest that, in drought years, losses could be reduced by shifting production from spring wheat to winter wheat. Overall, the impacts of long-term warming would be more pronounced in the northern agricultural zone of Saskatchewan. The provincial agroclimate and crop yields would become more homogeneous. Fifteen recommendations are made to improve climate impact assessment methodology and the use of impact information in agricultural planning and policy formation.

## ACKNOWLEDGMENT

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## 1. INTRODUCTION

The International Institute of Applied Systems Analysis/United Nations Environment Program (IIASA/UNEP) climate impacts project involved 76 authors in 17 countries. Their report, "The Impact of Climatic Variations on Agriculture" (1987), is in two volumes. The first deals with cold-margins; the second with warmer, semi-arid regions and mountainous areas in the tropics. Given its northern location and the sensitivity of its agricultural industry to climatic fluctuations, Canada was selected as a case study representing a cold-margin climate. The province of Saskatchewan, in particular, was selected because it is a major agricultural producer in Canada.

Within the context of the IIASA/UNEP climate impacts project, the objectives of this study were to:

1. Illustrate the applicability of several models in the impact analysis of climatic changes or fluctuations on Saskatchewan agriculture;
2. Quantify the impacts of specified climatic changes or fluctuations; and
3. Consider some of the more appropriate policy responses which would reduce negative impacts and maximize positive ones.

The Saskatchewan study did not attempt to assess the relative probabilities of different climatic scenarios. Instead, it concentrated on demonstrating techniques for translating climatic scenario information into assessments of the associated impacts on agriculture. A hierarchy of models was used to estimate impacts at various levels: "first-order" impacts on the agroclimatic environment and crop yields, and "downstream" or "second-order" impacts of these yield changes on farm production, employment, and the provincial economy. Results are intended to inform planners and policy makers of the agricultural implications of the latest climatological research. The study illustrates applications of historical and potential $CO_2$ warming scenarios and outlines some of the important climate-related problems affecting Saskatchewan agriculture.

The purpose of this paper is to provide a general summary of the Saskatchewan study. It comprises a brief summary of the methodology, highlights of the results, and the recommendations put forward for improving impact analysis and the use of impact analysis for policy formulation. For more detailed information concerning the Saskatchewan study, the reader is referred to Williams et. al. (1987).

## 2. METHODOLOGY

### 2.1 SCENARIO SELECTION

Climatic scenarios were selected to reflect issues of particular concern in the region and to enable comparisons to other case studies in the IIASA/UNEP project. These scenarios were constructed to represent future climates to test various methods of climatic impact assessment. Three broad types of scenarios were used: a single anomalous weather-year taken from the historical record, an extreme period of weather-years from historical records, and a future climate simulated using Goddard Institute for Space Studies (GISS) atmospheric general circulation model (GCM) results for 2 x $CO_2$. A standard climatic period, based on the 30 years 1951 to 1980, was used as a reference against which to compare results of analyses involving these scenarios. It is referred to as HIST1 (the following use of "HIST" refers to actual historical weather records). From the historical records, 1961 (HIST2) was selected as the extreme weather year, 1929 to 1938 as the extreme weather decade (HIST3), and 1933 to 1937 as the extreme weather pentad (HIST4). Each period was selected on the basis of drought severity and the substantive impact on crop yields, land degradation, and the economy in Saskatchewan. All historical climate data were obtained from the Atmospheric Environment Service, Environment Canada.

Data generated by the GISS GCM model for the equilibrium 1 x $CO_2$ or "control climate" (GISSE) and 2 x $CO_2$ (GISSC) climate were obtained from nine grid points covering the agricultural area of Saskatchewan. Analysis of the GISSE data for Saskatchewan showed little resemblance to the present climate. As a result, the actual GISS data could not be used in the study. To apply the GCM data, it was assumed that changes from GISSE to GISSC would correspond to changes expected for the climate of Saskatchewan given a doubling of atmospheric $CO_2$ concentrations.

To derive a climatic scenario for 2 x $CO_2$, designated here as GISS1, temperature increments corresponding to a doubling of $CO_2$, obtained by subtracting GISSE from GISSC temperature data, were applied to the 1951 to 1980 historical HIST1 data. Precipitation data were generated by dividing GISSC by GISSE precipitation data and applying the derived ratios to the HIST1 data.

The GISS model results indicate general increases of precipitation in Saskatchewan accompanying the increases in temperature with $CO_2$ doubling. Historically, low precipitation and high temperatures tend to occur in the same summers. Based on historical experience, it was assumed that warming due to $CO_2$ increases might occur without increased precipitation. To facilitate analysis of this possibility, an alternative scenario, GISS2, was used in which temperatures were increased (as with GISS1) but precipitation remained at the HIST1 level.

The GISS1 and GISS2 scenarios are simulations of average climates over a number of years. For impact analyses involving frequencies, such averages are not applicable. For the drought frequency analyses, data for individual years from 1950 to 1982 (HIST5) were used with adjustments derived from the changes from GISSE to GISSC to obtain 2 x $CO_2$ scenarios. The resulting scenario, GISS3, incorporates both temperature and precipitation changes. GISS4 is the year-by-year scenario for 1950 to 1982 that reflects only the temperature changes.

The scenarios used in this study are summarized in Table 1. For both the historical and GISS scenarios, only temperature and precipitation were adjusted. All other climate data required by the impact models were held constant at the HIST1 normal level. Where maximum and minimum temperature data were required, it was assumed that both were affected equally. Potential benefits of elevated $CO_2$ on plant photosynthetic capacity and moisture use efficiency were not considered in the biomass potential and the spring wheat model estimates because no consensus existed in the scientific community regarding the extent of the benefits. For the economic analysis, dollar values and technology were adjusted to represent 1980 conditions.

Table 1. Scenarios and variables used in the Saskatchewan case study.

| Scenario | Climatic Variables |
|---|---|
| HIST1: 1951 to 1980 normals | Tmax, Tmin, P, K, e, u |
| HIST2: 1961 | Tmax, Tmin, P |
| HIST3: 1929 to 1938 average | Tmax, Tmin, P |
| HIST4: 1933 to 1937 year by year | Tmax, Tmin, P |
| HIST5: 1950 to 1982 year by year | Tmax, Tmin, P |
| GISSE: GCM output for 1 x $CO_2$ | Tmax, Tmin, P |
| GISSC: GCM output for 2 x $CO_2$ | Tmax, Tmin, P |
| GISS1: | Tmax, Tmin, P adjusted from HIST1 |
| GISS2: | Tmax, Tmin adjusted from HIST1 |
| GISS3: | Tmax, Tmin, P adjusted from HIST5 |
| GISS4: | Tmax, Tmin adjusted from HIST5 |

Tmax = maximum air temperature, Tmin = minimum air temperature
P = precipitation, K = incoming solar radiation, e = vapour pressure,
u = windspeed

For all scenarios, e and u were held constant at the HIST1 level, and K at the 1967 to 1976 level.

For GISS1: T = GISSC - GISSE + HIST1 and P = (GISSC/GISSE) * HIST1; for GISS2: T = same as GISS1 and P = HIST1; for GISS3: T = GISSC - GISSE + HIST5 and P = (GISSC/GISSE) * HIST5; for GISS4: T = same as GISS3 and P = HIST5. T = Tmax, Tmin and Tmean (mean air temperature), respectively.

## 2.2 IMPACT MODELS USED

Impact models were selected using the following criteria:

1. Relevance to analysis of the impacts on Saskatchewan's agricultural productivity, the stability of the agroclimatic resource, or the conservation of the soil;
2. Suitability of the model for the particular application. The model had to have demonstrated applicability to macroscale analysis, and sensitivity to changes in the variables being analyzed; and
3. The capacity to provide information cheaply from readily available data.

The various impact models and the scenarios to which they were applied are listed in **Table 2**. Broadly speaking, the climatic change would impact on the agroclimate, which would impact on crop yields and the mix of crops grown, which would impact on the economy. Various models were used to look at the potential changes in each of these areas. For example, heat and moisture models (degree day, precipitation effectiveness, and Palmer Drought Index) were used to determine the impact on the provincial agroclimate. As well as changing the agroclimate, climatic change could impact on the productivity of the land base by accelerating or decelerating soil degradation processes. Wind erosion is a major component of Saskatchewan's climate-related soil degradation. In this study, a model adapted for calculating soil wind erosion potential was used to look at implications of climatic change for the land resource base.

The climatic changes implied in the scenarios selected would undoubtedly be followed by changes in the mix of crops grown in Saskatchewan. This could result in overall crop productivity being maintained or increased even though yields of present crops would decrease. A model developed by Turc and Lecerf (climatic index of agricultural potential), which estimates potential total dry matter biomass productivity, was selected to predict likely changes in productivity without specifying a particular crop.

To investigate the implications for specific crops, a crop growth model developed by Agriculture Canada was used to determine the impacts of

Table 2. Impact models and scenarios used in the Saskatchewan study.

| | Scenario | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | HIST | | | | | GISS | | | | | |
| Model | 1 | 2 | 3 | 4 | 5 | E | C | 1 | 2 | 3 | 4 |
| Growing degree-days | x | x | x | | | x | x | x | | | |
| Precipitation effectiveness | x | x | x | | | | | x | x | | |
| Palmer Drought Index | | | | | x | | | | | x | x |
| Climatic index of agricultural potential | x | x | x | | | | | x | x | | |
| Wind erosion potential | x | x | x | | | | | x | x | | |
| Spring wheat yield | x | x | | | x | | | x | x | | |
| Provincial agricultural economy | x | x | | | x | | | x | x | | |
| Provincial employmenbt | x | x | | | x | | | x | x | | |

climatic changes on spring wheat production. Economic implications of these changes on the provincial economy were then estimated using models developed by the Prairie Farm Rehabilitation Administration (PFRA). PFRA's models "track" the impacts resulting from changes in yields at the farm level through the entire agricultural sector at regional and provincial levels. Subsequent effects on non-agricultural sectors of the economy, at the regional and provincial levels are also examined.

## 3. RESULTS

Generalized results of the climatic impacts related to the various scenarios are presented in Table 3. In some instances, a range of values is given; in others there is only a single value. Where a range is given, the figures represent the maximum and minimum annual values computed over the period of record used. Where individual values are given, the period of record was treated as an average, or one year, and represents a long-term average (i.e., a 30-year average).

Results suggest that, without any fundamental change in climate, Saskatchewan agriculture can expect an occasional year (HIST2) with moisture resources so reduced that crop production is only about 25% of normal, the potential for wind erosion is doubled, and losses to the agricultural economy exceed $1.8 billion and 8000 jobs. Ripple effects in sectors other than agriculture translate into an additional provincial economic loss of $1.6 billion and 17 000 jobs. They also imply that in an extreme period of 5 to 10 consecutive years with warmer than normal growing seasons, moisture resources could be so sub-normal that biomass dry matter production could be reduced by nearly 50% and spring wheat production by about 20%. The impact of these climatic changes on the economy would be a direct loss to the agriculture sector of about 2600 jobs annually and an economic loss of nearly $600 million. This loss, resulting from effects on cereal crops alone, would have a further indirect effect on other sectors of the provincial economy causing an additional provincial gross domestic product (GDP) reduction of $500 million and 5600 jobs.

Table 3. Climatic impacts summarized for southern Saskatchewan in relation to normal (HIST1 or HIST5).

| | Scenario | | | |
|---|---|---|---|---|
| Model | HIST2 | HIST3 | GISS1 | GISS2 |
| Growing Degree Days | +10 to +18% | +3 to +16% | +48 to +53% | +48 to +53% |
| Precipitation Effectiveness | -18 to -53% | -21 to -26% | +1 to +13% | -10 to -12% |
| Biomass Potential | -53 to -100% | -26 to -60% | +1 to +30% | -19 to +3% |
| Wind Erosion Potential | +123% | - | -14% | +26% |

| | HIST2 | HIST4 | GISS1 | GISS2 |
|---|---|---|---|---|
| Spring Wheat Production | -76% | -20% | -18% | -28% |
| Expenditures by Agric. (million $) | -$1,810 | -$599 | -$163 | -$227 |
| Employment in Agriculture | -8,000 | -2,647 | -722 | -1,224 |

PALMER DROUGHT INDEX (PDI)

| | FREQUENCIES | | | RETURN PERIOD (YEARS) | |
|---|---|---|---|---|---|
| | HIST5 | GISS3 | GISS4 | HIST5 | GISS3 |
| Severe Drought | 0.1% | 0.9% | 10.8 | 15 to 35 | 8.5 to 17.5 |
| Drought | 3.0% | 9.1% | 39.6% | 6.5 to 10 | 4 to 6 |

With respect to the climate inferred for a 2 x $CO_2$ atmosphere, results suggest that on a long-term basis there would be a substantial increase in thermal resources, modest increases in moisture resources (according to the precipitation effectiveness index results) and potential biomass productivity, modest decreases in wind erosion potential and spring wheat productivity, and losses to the agricultural industry of about 700 jobs and $160 million annually. A further reduction in other sectors of the economy of about $150 million in provincial GDP and 1500 jobs annually could also be expected.

In contrast to the precipitation effectiveness results, results of the drought analysis indicate that the increase in precipitation projected by the GISS model would not be enough to offset the increase in evapotranspiration caused by higher temperatures. Apparently, the climate would shift to a more drought-prone regime, with an increase in length and frequency of droughts. Findings suggest a return period for what we presently call a "severe drought" of only about half as long as it is now (Table 3).

The drought and spring wheat analyses both suggest that the greatest impacts of $CO_2$ related warming would be in northern agricultural areas. Overall, the agroclimate and crop yields in Saskatchewan would be more homogeneous under a doubled $CO_2$ concentration atmosphere than they are now. The spring wheat analysis further emphasized the need to distinguish between individual and consecutive drought years. In the economic analysis, it was found that losses were considerably lower in drought years if the wheat crop mix was 10% winter wheat/90% spring wheat compared to 100% spring wheat. In normal years, however, it was found that producers would be better off economically if the entire crop was sown to spring wheat.

For a warmer climate inferred from 2 x $CO_2$, but without a precipitation increase (GISS2), results on a long-term average basis imply: moderate reductions in moisture resources and biomass and spring wheat productivity, a moderate increase in wind erosion potential, losses for the agricultural economy of about 1200 jobs and $275 million annually, and an additional decrease to the provincial GDP in non-agricultural sectors of approximately $250 million and 2600 jobs. A several-fold increase in drought frequency could be expected if the projected precipitation increase is not received (GISS4).

The results for GISS1 indicate that biomass potential would increase while wheat production would be reduced. This is reasonable because the long-term climate would change to the point where spring wheat would no longer be a well-adapted crop. A shift to a climatic regime with more frequent and severe droughts, as indicated by the drought analysis, could further accentuate problems with spring wheat production. The variability in yields would increase from year to year.

The results for GISS1 indicate that a more humid climate, as reflected in the higher precipitation effectiveness levels, would generally reduce the wind erosion potential. However, the accompanying increase in expected drought frequency and severity could increase the risk of serious wind erosion events. A shift to winter wheat, which leaves the ground covered during the erosion-prone spring period, could help reduce wind erosion potential. Results suggest that wind erosion potential would increase significantly with a change to a warmer climate without increased precipitation (GISS2). The likely reduction in biomass productivity and increase in drought frequency would accentuate this, although a shift from spring wheat to winter wheat could help limit wind erosion in spring.

## 4. RECOMMENDATIONS

The major problems in impacts research are that we don't really know how well the models work in assessing impacts, or whether any given scenario is a realistic representation of future climate. Consequently, a massive increase in the research effort directed at them is not likely to be very productive. It is felt that more progress could be achieved by concentrating on improving the analytical methods and making the whole process more objective.

Despite the inherent weaknesses in methods, this study provides some tentative answers to "What if..." questions about likely impacts on Saskatchewan agriculture of the particular historical and GCM-based scenarios considered. The results also demonstrate various methods that can be used for estimating impacts associated with new climatic scenarios that become available. Provided that the limitations of these methods are kept in mind, and care is taken in interpreting the derived information, they can, and should, be used to assist decision-making in agricultural planning and policy formulation. Based on the results of this study, eight recommendations are put forward for improving climatic impact analysis and seven for policy consideration.

## 4.1 RECOMMENDATIONS FOR IMPROVING CLIMATIC IMPACT ANALYSIS

1. Highest priority should be given to undertaking work that integrates impact assessment and climatic analysis.
2. Linkages among different impact models need to be developed.
3. Impact estimates should be made for a range of different crops and crop varieties.
4. The performance and sensitivity of various impact models should be examined and critically compared.
5. The study of soil degradation processes in the context of climatic impacts research should be substantially increased.
6. Tables showing various climatic change scenarios, impacts, and associated probabilities should be assembled.
7. More detailed consideration of the temporal and spatial variations of impacts would be desirable.
8. Analogue areas should be sought that have present climates comparable to the study area scenario climate.

## 4.2 RECOMMENDATIONS FOR POLICY

1. High priority should be given to supporting research to assess the likely impacts of climatic changes and fluctuations on agriculture.
2. Agricultural policy formulation and planning should be carried out with full awareness of the implications of a changing climate for agriculture.
3. Agencies involved in policy formulation and planning, with respect to Saskatchewan agriculture, should take the set of

impact results for each scenario in this case study and work out the appropriate policy package for each circumstance.

4. Research into the combined impacts of the direct effects of increasing $CO_2$ on agriculture, and the climatic effects, should be supported.
5. Consideration should be given to whether the prospects for a major change in Saskatchewan's climate now seem likely enough to justify intensification of strategies to help agriculture make the best use of the agroclimatic resources.
6. Agricultural extension activities should be expanded to provide information required by producers to take advantage of beneficial climatic changes and minimize the impacts of detrimental ones.
7. Assessments of the costs and benefits to Saskatchewan agriculture of various responses to the climatic changes analyzed in this study should be undertaken.

## 5. REFERENCE

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# CLIMATIC TRENDS AND THE EFFECTS OF WEATHER VARIABILITY ON WHEAT YIELDS ON THE CANADIAN PRAIRIES[1]

by

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## ABSTRACT

While climatic change is a topical subject, it is important that some attention is relegated to present-day problems. Climate variability and trends are important factors in assessing the current economics of Prairie wheat production. Changes in wheat yields, with time, are due to both weather and non-weather factors, such as changing farm technology and relatively slow changes in soil properties. A mathematical model was used to analyze 22 years of data (1961 to 1982) to separate weather from non-weather effects using approximately 100 weather stations distributed in the wheat-growing areas of the Canadian Prairies. A non-linear time trend was calculated which indicated that yields have increased by about 40% over this period, due to non-weather factors, but that these non-weather effects were levelling off or becoming constant in the late 1970s and early 1980s. Then the model was used to calculate yields using long-term (40 to 60 years) weather records. These long-term sequences of yield were used to calculate probability distributions of yields. These sequences indicated that long-term trends in weather are small compared to annual variability. There also seems to be an 18- to 19-year cycle in these trends, but this cycle accounts for a very small part of the year-to-year variability.

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[1] L.R.R.C. Contribution No. 87-97

## 1. INTRODUCTION

Hard red spring wheat is the leading export crop in Canada. Most of this crop is grown in the prairie provinces. This region lies in the rain shadow of the Western Cordillera. Thus, the rainfall is both sparse and variable. This region is also susceptible to the southward movement of polar air masses. Therefore, this main wheat growing area in Canada is susceptible to droughts and both late spring and early fall frosts. It is not surprising that crop yields vary markedly from year to year.

Quantifying this variability in yields is important in assessing the region's productivity. Average yield levels are less useful than a range of yield probabilities. However, a large number of years, 40 to 60 minimum, are needed to calculate these probabilities. Given this time frame, yield levels will change due to technological advances. Thus, yield data are difficult to use for calculating probabilities, particularly since it is the probability of yields using present-day technology that is needed.

In this study, a mathematical model was used to characterize the effect of recent technological changes on crop district yield data. By setting trend coefficients at present-day values, the model was used to calculate yields from long-term weather records. These time series of yields were used both to calculate yield probabilities and to study long-term weather effects on yields.

## 2. SEPARATING WEATHER AND TECHNOLOGICAL FACTORS

While weather is a primary influence on year-to-year changes in yields, there are other factors which change, in a cumulative way, relatively slowly with time. These factors include the increased use of fertilizers and herbicides, use of new varieties and changes in soil property, and organic matter. Stewart and Dwyer (1987a, 1987b) describe a mathematical model which separates out the confounding effects of weather and non-weather factors. The model uses weather data in the form of daily maximum and minimum air temperatures, and daily precipitation, to calculate a yield value. Subject to the limitations of the model, variations in weather were accounted for directly in the calculations of the model. However, some empiricism is inherent in the model. As well, the slow-changing non-weather factors are described by empirical equations. Thus, some calibration with actual yield data is necessary.

A 22-year period from 1961 to 1982 was chosen for data analysis. Data sets included crop yield and seeded acreages of summerfallow and stubble, for crop districts in Saskatchewan and Manitoba and census divisions in Alberta. These data were obtained from Statistics Canada. Weather data for this period were obtained from the archived data sets at the Land Resource Research Centre, Agriculture Canada, Ottawa. These data originally came from the Atmospheric Environment Centre, Environment Canada (Anonymous 1982). The Theissen polygon method (Hayhoe and Williams 1982) was used to weight the weather station data to calculate a weather record for each crop district.

The model used the method of Williams and Robertson (1965) to estimate both the yield of wheat seeded into summerfallow ($Y_F$, kg/ha) and into stubble ($Y_S$, kg/ha). It used moisture conserved from the previous September in the case of stubble yields and from the September of one year previous plus a year of fallow for the case of summerfallow years. The average yield for a given year (t) and crop district (j) was described by:

$$Y_{t,j} = a_j \, [P_{t,j} \, Y_{Fi,j} + (1-P_{t,j}) \, Y_{Si,j}] + c_j \, t - c_j t^2/2T \qquad \text{(Eq. 1)}$$

where P is the proportion of crop seeded into summerfallow, t is time in years, T is the total number of years in the period minus one (21 years), a is an empirical coefficient for each crop district, and c is an empirical time coefficient which varies with crop district (P varies with both time and district). Values of a, c, and certain growth coefficients in the model were calculated by fitting equation (1) to the yield data using non-linear, least squares analysis (Stewart and Dwyer 1987a, 1987b).

Crop districts were grouped into the three soil zones as described by Williams et al. (1975). These zones were designated as Brown, Dark Brown, and Black. Fitting equation (1) to the data resulted in correlation coefficients of 0.94, 0.88, and 0.87, and standard errors of estimate of 124.6, 194.7, and 209.2 kg/ha, for the Brown, Dark Brown, and Black zones, respectively. Both calculated and actual yields were averaged by crop district for each of the three major soil zones and for each year. Differences between actual and calculated yields are plotted in **Figures 1a, 1b, and 1c** where the calculated yields use equation (1) without the time trend components (i.e., the last two terms in equation (1) were set to zero). These differences increase with time because the time trend is not included in the calculations. The solid lines in Figure 1 represent the time function $(ct-ct^2/2T)$ where c is averaged for each zone. Thus, Figure 1 shows the smoothed representation of non-weather time trends with the data from which these trends were derived. The data show that Stewart and Dwyer's (1978b) time function was appropriate. For all zones, yields increased from 1961 to 1975 with a levelling off from 1976 to 1982.

A total increase in yields from 1961 to 1982 can be calculated from the time function with $t = 21$ years. A range of these increases can also be calculated using the standard error of the coefficient c. That is,

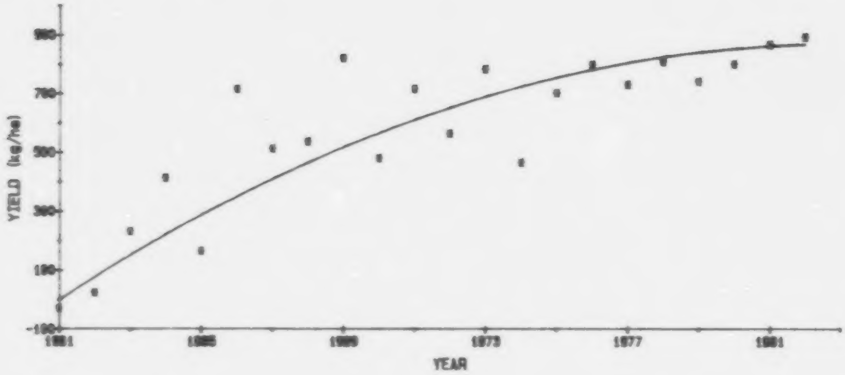
$$\Delta = 10.5\ (c \pm SE) \qquad \text{(Eq. 2)}$$

where $\Delta$ is the increase in each zone and SE is the average standard error of c for each zone. Values of $\Delta$ with its range are listed in Table 1. The largest yield increase occurs in the Brown soil zone followed by the Dark Brown and Black. However, differences between zones are small and all ranges overlap. Thus, non-weather factors seem to be of the same magnitude in all zones.

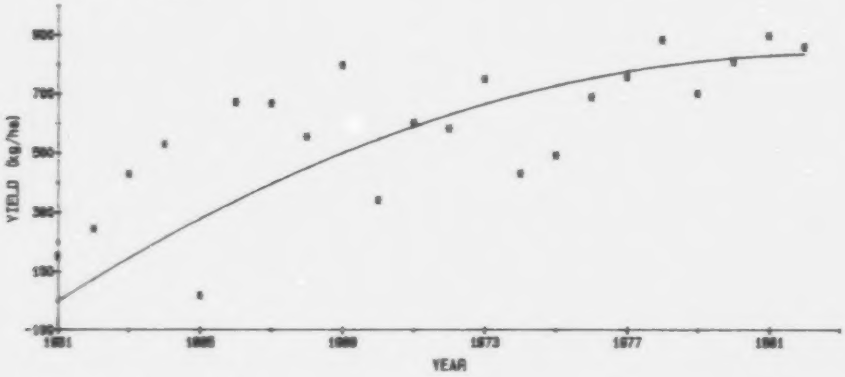
There are many reasons for yield increases between 1961 and 1982. Weed control, larger and more efficient machinery, new crop varieties, and increased use of fertilizers could cause such an increase. The levelling off between 1976 and 1982 is harder to explain. Fertilizer use, for example, continued to increase during this period (Fertilizer Institute of Canada).

The possibility exists that the increased use of fertilizer is just compensating for a decrease in inherent soil fertility. This is only speculation and more research is needed to determine the cause of this levelling off of crop yields with time.

a) Brown



b) Dark Brown



c) Black

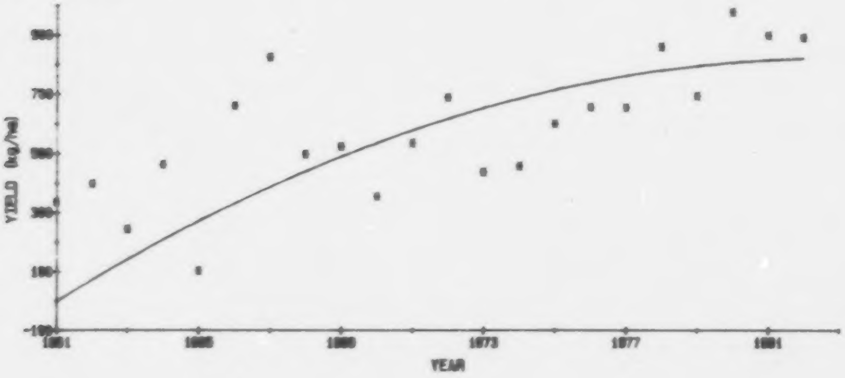


Figure 1. Difference between observations and calculated yields using eq. (1) with $t = 0$ for the three major soil zones. The solid line in each graph is the time function ($ct-ct^2/2T$) with $c$ averaged for each soil zone.

Table 1. Mean and range of the time trend coefficient, c, and of , the total calculated change in yield and percent protein due to time trends.

| Soil Zone | c | Yield (kg/ha)<br>Δ |
|---|---|---|
| Brown | 79.10 ± 12.64 | 830.6 ± 132.7 |
| Dark Brown | 76.27 ± 16.56 | 800.8 ± 173.9 |
| Black | 74.88 ± 19.31 | 786.2 ± 202.8 |

## 3. YIELD PROBABILITIES

From Figure 1 we can see that yields do change with time, but these changes were very small in 1982. Yield calculations at the 1982 levels can represent present-day technology. By using long-term weather records we can calculate time sequences of yields using equation (1), which in turn can be used to calculate yield probabilities. These time sequences also simply reflect how weather changes with time since the model integrates the weather variables into one value per year.

Equation (1) was first modified to

$$\overline{Y}_j = a_j [\overline{P}_j Y_F + (1-\overline{P}_j) Y_S] + 10.5 c_j \qquad \text{(Eq. 3)}$$

where j is set to equal 21 years.

Values of $a_j$ and $c_j$ were taken from calculated values for the crop district where the weather station was located. Values of $\overline{P}_j$ were calculated by averaging P over 1980, 1981, and 1982 in each crop district. The problem with equation (3) is that values of $\overline{Y}$ cannot fall below 10.5 $c_j$. This is a serious limitation in dry years. Instead, the following equations were used:

$$Y_i = a_j (\overline{P}_j Y_{Fi} + (1-\overline{P}_j) Y_{Si}) Y_{M1}/Y_{M2} \qquad \text{(Eq. 4)}$$

where $$Y_{M1} = \sum_{i=1}^{M} a_j (\overline{P}_j Y_{Fi} + (1-\overline{P}_j) Y_{Si}) + 10.5 c_j \qquad \text{(Eq. 5)}$$

and $$Y_{M2} = \sum_{i=1}^{M} a_j (\overline{P}_j Y_{Fi} + (1-\overline{P}_j) Y_{Si}) \qquad \text{(Eq. 6)}$$

and where M is the number of years in the extended time period.

Equation (3) consists of two parts: the basic model which calculates yield at 1961 conditions, and the time trend term (10.5 $c_j$) which extended the calculations to 1982 conditions. To avoid using an additive term, the multiplicative term $Y_{M1}/Y_{M2}$ was developed. It is an average of calculated yields at 1982 conditions divided by the average calculated yields at the 1961 conditions. If growing conditions were so severe that both $Y_{Fi}$ and $Y_{Si}$ were zero, equation (2) would still show a yield equal to 10.5 $c_j$, which according to Table 1 is between 786 and 830 kg/ha. Equation (4), on the other hand, gives the expected value of zero. For a given location over a longer period of years, equations (3) and (4) would give the same average yield. However, over such a time sequence, extremely dry years would be encountered, and equation (4) would produce a more realistic probability distribution.

For this study of yield probabilities, records from 27 weather stations, distributed throughout the prairie wheat-growing region, and with extended time coverage (40 to 60) years, were obtained from the same source as the technology trend study. These stations were grouped into five soil zones. The Black soil zone, used previously, was subdivided into three black soil zones, one in each of Alberta, Saskatchewan, and Manitoba. Time sequences of yields were calculated for each zone using equation (4). Values of a, c, and P were taken from the crop district where the weather station was located. For a given location, yields for a crop summerfallow rotation ($Y_F$) and for continuous cropping ($Y_S$) were calculated. Then they were weighted by $\overline{P}_j$ (the proportion of land seeded into summerfallow) and $(1-\overline{P}_j)$ respectively and multiplied by $a_j$, a location specific coefficient. These yields can be thought of as 'weighted' yields and will be referred to by this term.

There is considerable interest in probabilities of yields for continuous cropping (stubble yields). Summerfallow may contribute to soil organic matter degradation, wind erosion, and increased salinization. However, cessation of summerfallow increases the risk of crop failures due to drought. Therefore, a quantitative assessment of these risk increases is important. To calculate stubble yields, $\overline{P}_j$ is set to equal zero in equation (3). Stubble yields calculated in this way were compared to actual stubble yields for crop districts in Saskatchewan (D.W. Stewart, unpublished study 1985).

For each type of yield calculation (weighted and stubble), yields were ranked over each time period, M, in ascending order. The value for a given probability level, k, was determined as follows. The kth probability is the k (N+1)/100th observation (Anonymous 1982). If this is not a whole number, a linear interpolation is made between the ranked values on either side of the observation. For example, if the 20 percent probability is the 9.5th observation, then the yield value at this probability is midway between the 9th and 10th ranked observations.

Average yields and the probability of obtaining 1000 kg/ha or less are tabulated, by soil zone, in **Table 2** for both weighted and stubble conditions (1000 kg/ha was chosen because it is about one half the weighted yield averages). Weighted yields tend to increase with the darkness of the soil. Differences are relatively small, however, due to the greater use of summerfallow in the lighter-coloured soil zones. A similar trend can be seen for the weighted probabilities. However, of special interest is the very low probability (6.1%) in the Black soil zone of Alberta. This low probability reflects the most stable climate of the five zones. This condition is also evident from yield projections by Stewart and Dwyer (1987a).

Larger differences between zones are evident in the calculations for stubble (Table 2). One of the reasons for summerfallow crop rotation is to decrease the risk of crop failure. Thus, it is not surprising that the probabilities of attaining yields less than 1000 kg/ha double with continuous cropping. However, they are much lower in absolute terms in the Black soil zones. It is likely that a farmer could tolerate a 10 to 15% probability of a less than 1000 kg/ha yield in the Black soils zones of Alberta and Manitoba but not the 30 to 40% probability in the Brown and Dark Brown soil zones. The Black soil zone of Saskatchewan at 22% is in between. This high probability of low yield soil zone reflects the greater use of summerfallow in the Black soil zone of Saskatchewan as compared with the Black soil zones of Alberta and Manitoba.

## 4. TIME SEQUENCES OF YIELDS

Yields that were used for probability calculations were plotted against time for both weighted and stubble cases for the five soil zones in **Figures 2a, 2b, 2c, 2d,** and **2e**. Five-year moving averages are also shown. A yield calculation for a given year integrates various weather

Table 2. Yields averaged over time with the probability of less than 1000 kg/ha yields for each weather station. Values are given for crops with the weighted effect of summerfallow and for continuous cropping (stubble).

| | | WEIGHTED | | STUBBLE | |
|---|---|---|---|---|---|
| Soil Zone | Station | Yield kg/ha | Prob. of 1000 kg/ha or Less | Yield kg/ha | Prob. of 1000 kg/ha or Less |
| Brown | Kindersly | 1957 | 20.3 | 1364 | 39.3 |
| | Swift Current | 1971 | 14.6 | 1492 | 34.5 |
| | Anervid | 1769 | 25.2 | 1317 | 48.6 |
| | Brooks | 2224 | 12.2 | 1796 | 22.3 |
| | Medicine Hat | 2163 | 10.8 | 1709 | 30.8 |
| | Manyberries | 1703 | 18.6 | 1263 | 44.2 |
| | Val Marie | 1604 | 33.2 | 1172 | 53.2 |
| | | 1913 | 19.3 | 1445 | 40.0 |
| Dark Brown | Midale | 1876 | 15.8 | 1553 | 28.6 |
| | Hanna | 1723 | 16.8 | 1302 | 41.7 |
| | Tugaske | 1963 | 14.1 | 1478 | 39.5 |
| | Scott | 2085 | 16.7 | 1584 | 24.8 |
| | Saskatoon | 1867 | 7.0 | 1390 | 31.8 |
| | Regina | 2012 | 21.3 | 1625 | 25.7 |
| | Lethbridge | 2022 | 9.3 | 1679 | 29.4 |
| | | 1935 | 14.4 | 1516 | 31.6 |
| Black Alberta | Olds | 2331 | 4.1 | 2203 | 11.3 |
| | Lacombe | 2213 | 8.0 | 2132 | 7.0 |
| | Ranfurly | 2079 | 7.7 | 1833 | 16.8 |
| | Beaverlodge | 2116 | 4.4 | 1932 | 7.6 |
| | | 2185 | 6.1 | 2025 | 10.7 |
| Black Sask. | Prince Albert | 1905 | 12.3 | 1565 | 27.8 |
| | Melfort | 2169 | 12.4 | 1816 | 22.7 |
| | Indian Head | 2082 | 12.6 | 1750 | 22.2 |
| | Yorkton | 1938 | 16.1 | 1662 | 16.6 |
| | | 2024 | 13.4 | 1698 | 22.3 |
| Black Manitoba | Birtle | 2133 | 12.1 | 1920 | 21.3 |
| | Brandon | 1989 | 13.9 | 1880 | 17.9 |
| | Waskada | 1904 | 15.6 | 1770 | 21.4 |
| | Mordon | 1949 | 12.3 | 1895 | 14.0 |
| | Winnipeg | 1904 | 5.5 | 1827 | 5.0 |
| | | 1976 | 11.9 | 1858 | 15.9 |

Figure 2(a) Brown

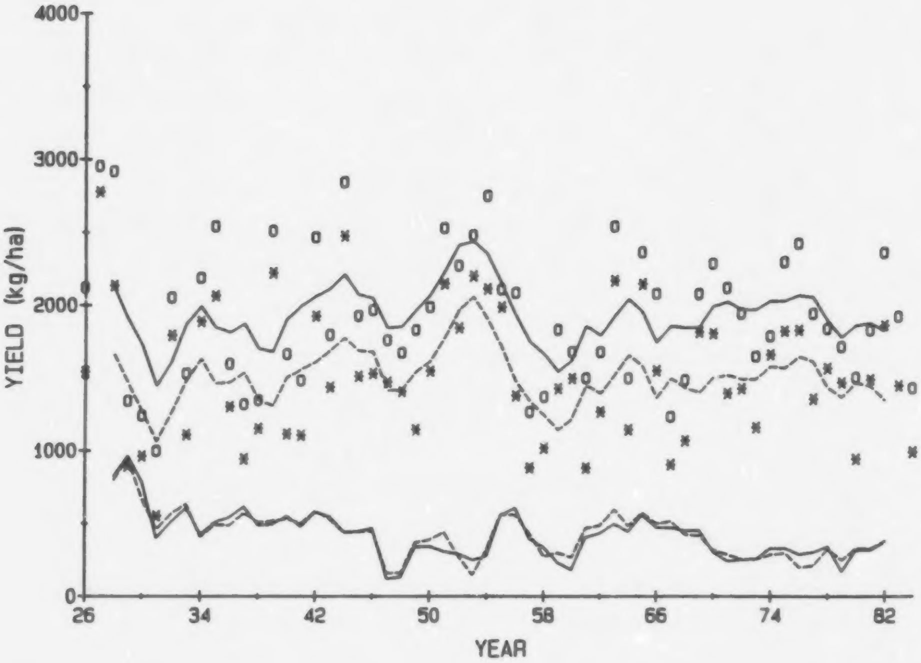


Figure 2a. Time sequences of yields over 60 years for Brown soil zone. Symbols are as follows:

- * represents weighted yields
- 0 represents stubble yields
- solid upper line represents 5-year moving mean for weighted yields.
- dotted upper line represents 5-year moving mean for stubble yields.
- solid lower line represents the standard deviation of the 5-year moving mean for weighted yields.
- dotted lower line represents the standard deviation of the 5-year moving mean for stubble yields.

Figure 2(b) Dark Brown

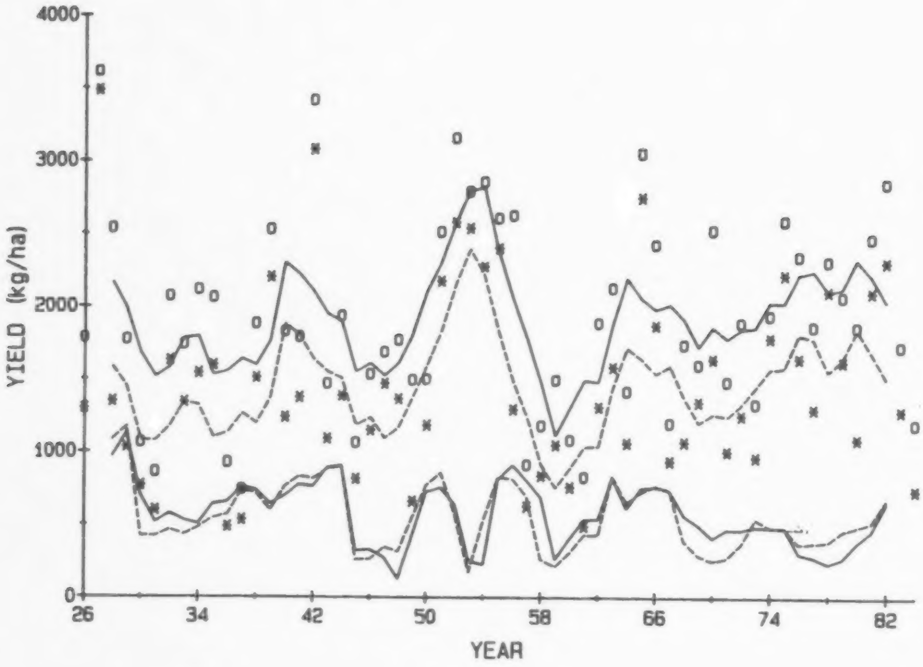


Figure 2b. Time sequences of yields over 60 years for Dark Brown soil zone. Symbols are as follows:

- * represents weighted yields
- 0 represents stubble yields
- solid upper line represents 5-year moving mean for weighted yields.
- dotted upper line represents 5-year moving mean for stubble yields.
- solid lower line represents the standard deviation of the 5-year moving mean for weighted yields.
- dotted lower line represents the standard deviation of the 5-year moving mean for stubble yields.

Figure 2(c) Black Alberta

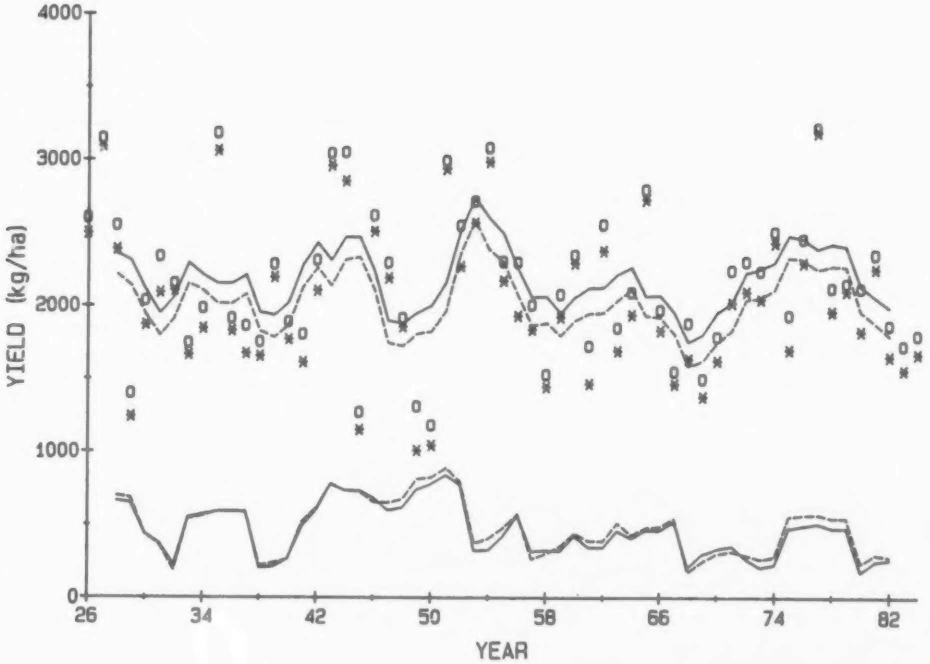


Figure 2c. Time sequences of yields over 60 years for Black Alberta soil zone. Symbols are as follows:

- * represents weighted yields
- 0 represents stubble yields
- solid upper line represents 5-year moving mean for weighted yields.
- dotted upper line represents 5-year moving mean for stubble yields.
- solid lower line represents the standard deviation of the 5-year moving mean for weighted yields.
- dotted lower line represents the standard deviation of the 5-year moving mean for stubble yields.

Figure 2(d) Black Saskatchewan

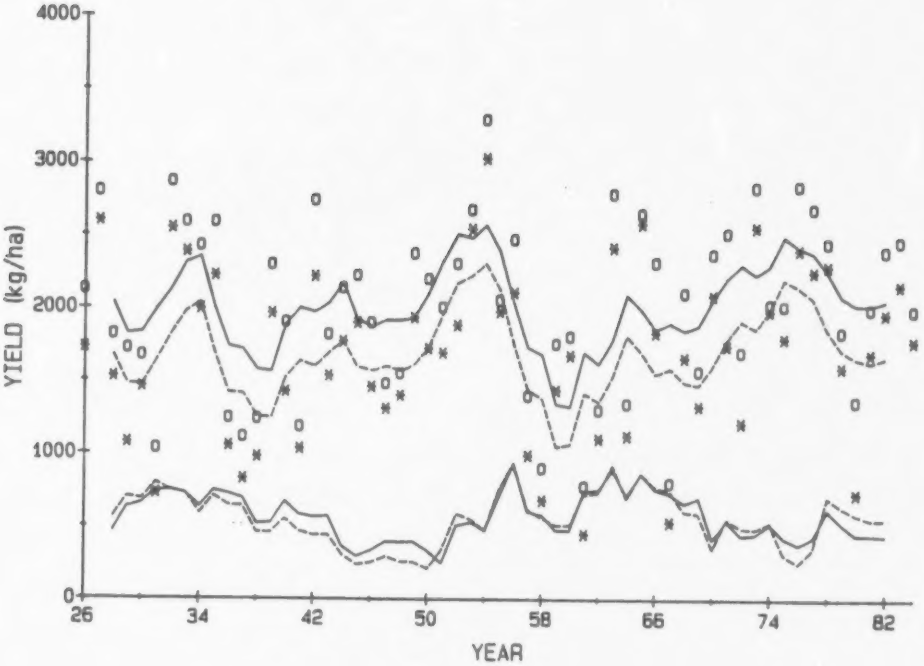


Figure 2d. Time sequences of yields over 60 years for Black Saskatchewan soil zone. Symbols are as follows:

- * represents weighted yields
- 0 represents stubble yields
- solid upper line represents 5-year moving mean for weighted yields.
- dotted upper line represents 5-year moving mean for stubble yields.
- solid lower line represents the standard deviation of the 5-year moving mean for weighted yields.
- dotted lower line represents the standard deviation of the 5-year moving mean for stubble yields.

Figure 2(e) Black Manitoba

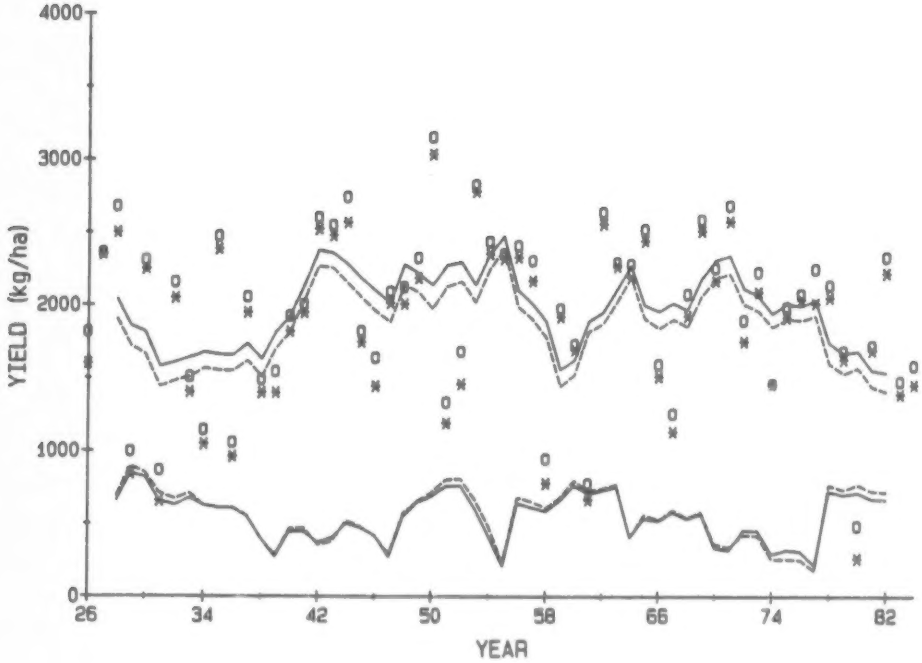


Figure 2e. Time sequences of yields over 60 years for Black Manitoba soil zone. Symbols are as follows:

- * represents weighted yields
- 0 represents stubble yields
- solid upper line represents 5-year moving mean for weighted yields.
- dotted upper line represents 5-year moving mean for stubble yields.
- solid lower line represents the standard deviation of the 5-year moving mean for weighted yields.
- dotted lower line represents the standard deviation of the 5-year moving mean for stubble yields.

factors into a single value or two values if the stubble situation is also calculated. Thus, these yield sequences over time are a useful way to study trends in weather. Since all calculations are done at the 1982 level of technology, technological change is not a factor influencing yields.

There are a number of phenomena shown in these time sequences. The influence of the droughts in the 1930s, early 1960s and, to a lesser extent, the early 1980s is evident. The early 1930s drought was most severe in the Brown and Dark Brown soil zones. It was least severe in the Black soil zones of Alberta and Saskatchewan. The relative stability of yields in the Black soil zone of Alberta is evident. There is no clear time trend in yields in these graphs, indicating that yields are not increasing or decreasing due to climatic change. Also shown are the standard deviations of the five values used to calculate each of the moving averages. From 1966 onward, there seems to be a tendency for a reduced variability in yields. The period from 1966 to 1982 seemed to be relatively stable weatherwise, particularly in the Brown and Dark Brown soil zones.

The most interesting aspect of these time sequences is a tendency toward cycles. These are most evident in the Black soil zone of Saskatchewan. Droughts occurred in the late 1930s, early 1960s, and the early 1980s, reflecting an 18- to 22-year cycle. Cycles of this length were also observed by Currie and Hameed (1986) for corn yield in Iowa and Illinois. The early 1930s drought, most evident in the Brown and Dark Brown soil zones, does not fit into this cyclical pattern. Studies are underway to measure these cycles using spectral analysis. The above procedure for calculating probabilities assumed that weather events are not related from one year to the next. Presence of cycles would mean that probability distributions would change with time.

Another factor which could influence yield probabilities is climatic change itself. We will have to reassess the way we use long-term weather records if anthropogenic factors are changing the climate. Trend analysis on such data, as shown in Figure 2, will be very important. It is evident, however, that there is no clear trend to date on the weather factors which affect yield as calculated by the mathematical model.

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# CLIMATE VARIABILITY - THE IMMEDIATE CONCERN FOR PRAIRIE AGRICULTURE

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## ABSTRACT

It is suggested that climate variability is of equal, if not greater, concern than climatic change in terms of its impact on agriculture. Through the use of agroclimatic parameters, the magnitude of climate variability and its impact on agriculture are described. It is important that we increase our awareness of the current effects of climate variability. The likelihood of increased variability associated with long-term climatic change means its importance in policy planning and development becomes critical.

## 1. INTRODUCTION

The subject of climate variability seems always to be in a position of "second fiddle" to that of climatic change. Sometimes a study of climatic change leads to the discovery of the importance of climate variability. This is evident from the proceedings of a conference on "Climate Change, Food Production and Interstate Conflict" held in Bellagio, Italy in 1975 (Lansford 1975). (Since that time the consensus among climatic change experts has swung from predictions of an imminent ice age to the now in-vogue "Greenhouse" warming theory.) A conclusion at that conference, which is relevant to our discussions, was that "temperature change *per se* is not the most serious potential threat to food production." By contrast, "climate variability . . . poses threats to agricultural production." Our purpose is to use some prairie and Manitoba data to demonstrate the magnitude of variability of climatic characteristics relevant to agriculture and ask you to consider whether or not that conclusion is also appropriate to our meeting.

Before moving into our discussion of the impact of agroclimate variability, it may be appropriate to highlight the significance of agriculture in Manitoba. In 1985, agriculture accounted for $2.7 billion of the province's gross domestic product (GDP) or 16.6% of the total GDP, and directly or indirectly generated 84 300 jobs (17.6% of the total employed labour force). Manitoba's agricultural activity contributed over $4.2 billion to Canada's GDP and accounted for over 114 000 jobs (Manitoba Bureau of Statistics 1987). Thus, in considering the effects of weather and/or climate on agriculture and agricultural production, the social, economic, and political impacts on Manitoba and Canada are profound. As Rosenberg (1986) states: "agriculture is the human enterprise most sensitive to change in general climatic conditions and climate variability."

Far too often, recommendations for agriculture are made on the basis of average values or "normals." Unfortunately, whereas the word "normal" in everyday conversation means "usual", in climatology it means "statistical average." This leads to considerable misunderstanding of "climatic normals" by the general public. This can be a very bad practice. To illustrate, let us assume we want to know how much irrigation would be required in Lethbridge during the month of May. It would be important for us to know how much precipitation to expect. Naturally, we would ask for the average May rainfall for Lethbridge. However, we would be led down the garden path by this information. As shown in Figure 1, Lethbridge gets less than its average May precipitation almost 70% of the time (Shaykewich et al. 1985). The rainfall does not follow a normal frequency distribution. It would probably be more useful to know the largest amount of precipitation we could expect 50% of the time. Thus, particularly for weather characteristics relating to a short time span, such as monthly precipitation, it is important to know both mean values and frequency distributions.

## 2. THE IMPORTANCE OF CLIMATE VARIABILITY

Before we can discuss the importance of climate variability to agriculture, we must define variability, or at least what kind of variability we should be concerned about. If beauty is in the eye of the beholder, then variability is in the eye of the user. In other words, a characteristic has the potential for being variable only if it has some influence on the subject we are studying. In agriculture, this means that there must be a biological and operational sensitivity to a particular climatic characteristic before we care whether or not it is variable. For example, a knowledge of random variability in mean annual temperature is of no value to agriculture. The correlation of mean annual temperature to conditions during the growing season, which on the Prairies is less than 30% of the year, is simply not good enough to be of any value. By contrast, variation in the frost-free period, which defines the growing season, is of considerable interest.

Part of the problem is that people do not believe that large variations in climate exist. When it comes to weather, people have incredibly short memories. For example, the frost on 26 August 1982, which hit most of Western Canada, was certainly considered to be an unusual event. If we check the climatic record, however, we find that it was not unusual at all. For instance, the data for the Agriculture Canada station at Brandon, Manitoba, show the following dates for the first autumn frost:

1934 - August 28
1941 - August 27

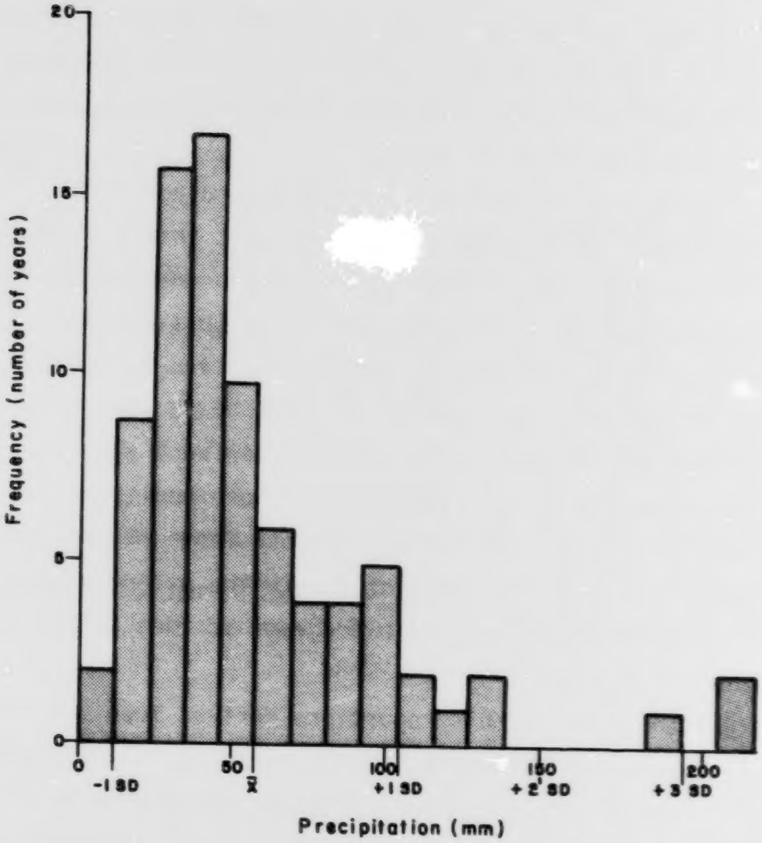

Figure 1. Frequency distribution of rainfall for the month of May for 81 years at Lethbridge. Mean = 55.6 mm; SD = 45.9

1964 - August 15
1968 - August 16
1977 - August 18

On the average, the first autumn frost in Brandon occurs on September 11. Thus, in the last 50 years, we have had the first frost in autumn occur 6 times on or before August 28. How many farmers around Brandon would know this?

There is a program that is supposed to protect farmers against weather variability; namely, Crop Insurance. That this program is vital is illustrated by the magnitude of crop losses due to adverse weather (Table 1). However, it seems that all too often this program is inadequate. For example, in 1984 to 1985, $8 million were provided for field crop producers in Manitoba and northeast Saskatchewan for crop losses caused by excess moisture. In 1985 to 1986, $64 million were allocated for drought assistance for Western Canada. These amounts were additional to those provided under the Crop Insurance Act. Perhaps those responsible for crop insurance should become better acquainted with the extent of weather variability. They should design their programs so that ad-hoc government assistance is not necessary.

Most of the data in this report are derived from a study by Dunlop (1981). In this study, weather stations in agricultural Manitoba with a minimum 15-year record were used. All available data between 1929 and 1978 were analyzed for each station. A number of climatic characteristics of significance to agriculture were calculated; viz., frost dates in spring and fall, frost-free period, degree days, corn heat units, and estimates of soil moisture status under various agricultural crops.

The frost ($0^oC$) data provide us with a perspective on climate variability as it applies to agriculture. For example, the average date of the first fall frost in agro-Manitoba ranges from September 4 to September 24. Along with averages, standard deviations for each weather station were calculated. The average of these standard deviations is about 11 days. However, the amount of variability from the mean is remarkably similar throughout the province. This is shown by the fact that the standard deviation of these standard deviations is only about three days. The

Table 1. Values of crop losses in Manitoba due to adverse weather.[a]

| Climate Condition | 1985 | 1984 | 1983 | 1982 |
|---|---|---|---|---|
| Frost | 10 281 932 | 278 320 | 212 542 | 11 667 953 |
| Excess Moisture | 5 946 983 | 1 591 708 | 2 842 831 | 1 095 840 |
| Wind | 5 319 024 | 1 494 607 | 753 466 | 123 790 |
| Drought | 2 508 534 | 10 573 866 | 5 343 864 | 1 631 286 |
| Hail | 412 462 | 1 153 102 | 855 815 | 992 503 |
| Heat | - | 1 002 923 | 4 152 090 | 7 030 |
| All Causes | 26 611 068 | 17 482 451 | 15 086 410 | 16 712 673 |

[a] These numbers do not include losses due to hail spot losses or unseeded acreage.
Value reported in Canadian dollars.
Source: Manitoba Crop Insurance Annual Reports, 1982 to 1985.

disturbing statistic, however, is that, one third of the time, the first fall frost occurs on a date which is more than 11 days before or after the mean. It is evident that the mean is not the only information we should be providing farmers. It is much more useful to provide them with risk maps. For example, a map for Manitoba (**Figure 2a**) shows when the risk of frost has been reduced to 10%. This map is vastly different from that showing the average date of fall frost (**Figure 2b**). At Brandon, the 10% risk date is approximately August 28, while the average date of frost is September 11.

Similar comments can be made about the frost-free period, which determines the growing season for many agricultural crops. Again using Brandon as an example, we find the average length of the frost-free period is about 105 days (**Figure 3a**). However, in one year in four, we can expect it to be 93 days or shorter (**Figure 3b**). Thus, many crops that would reach maturity at Brandon "on the average," cannot be grown because in many years they would not reach maturity.

## 3. WATER STRESS IN THE PRODUCTION OF WHEAT

Water stress in wheat production is governed by: (1) the amount of water required to grow the crop, (2) the amount of water in the soil at the start of the growing season, and (3) the amount of water supplied by precipitation. The amount of water used by the crop at various times in the growing season is determined by: (1) potential evapotranspiration, and (2) the ratio of potential water use by the crop to potential evapotranspiration -- a consumptive use factor (CU). For this study, potential evapotranspiration was calculated using a method developed by Baier and Robertson (1965). Consumptive use factors for wheat were based on data presented by Hobbs and Krogman (1968) (**Figure 4**). The growth stages used by Hobbs and Krogman were translated into biometeorological time as defined by Robertson (1968). All these relationships were applied to historical planting dates and daily weather data from climatological stations in Manitoba to estimate water use by wheat from planting to maturity. The results of these calculations, for Brandon Airport data, are shown in **Figure 5**. Between 1948 and 1982, it is estimated that the amount of water required to mature wheat at this location varied between 270 and 360 mm annually, with an average of 308 mm. The range of water requirement is nearly one third of the mean.

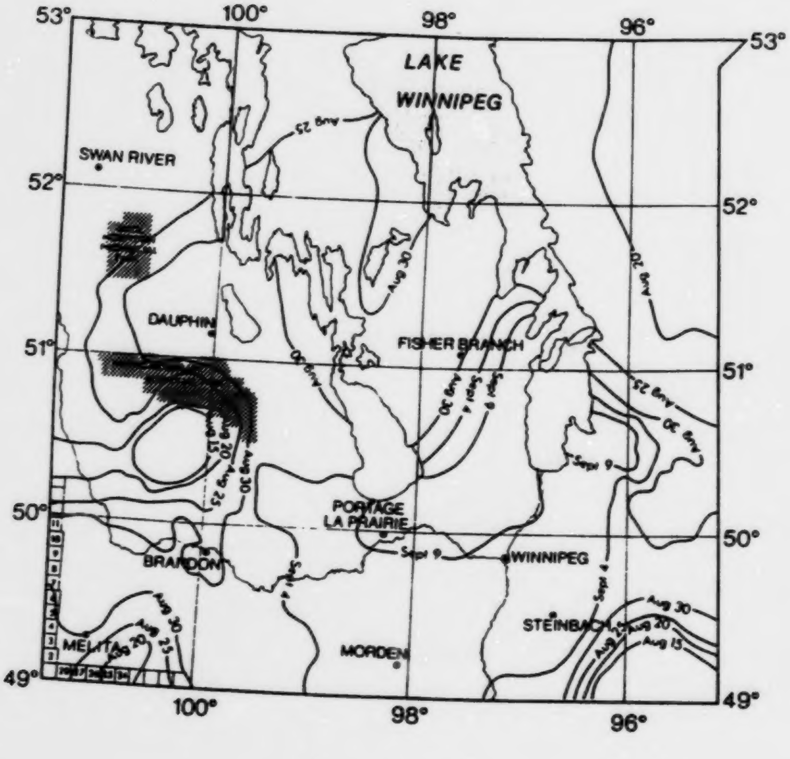
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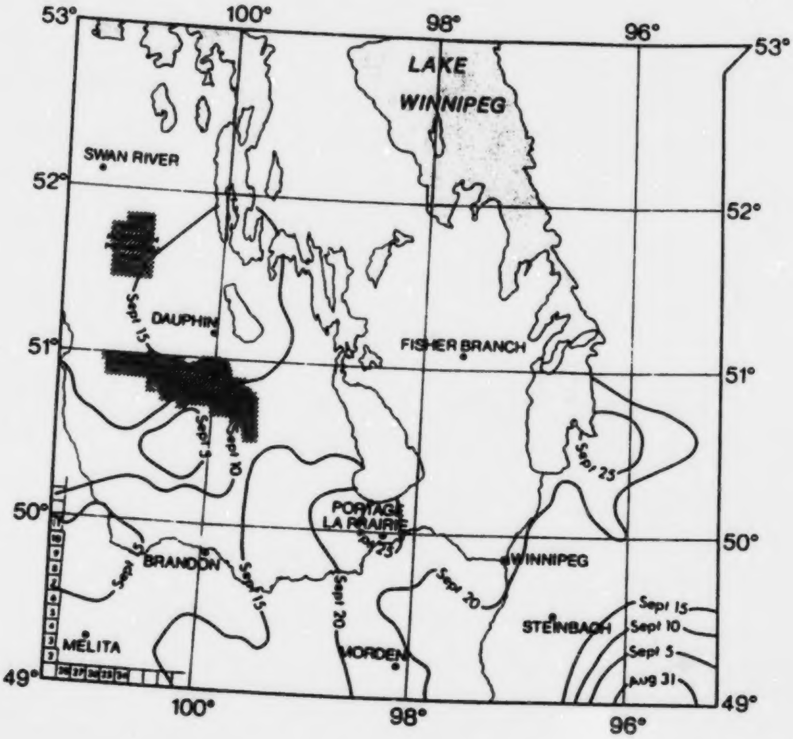
Figure 2a. Dates before which the occurrence of the first fall frost (0°C) is at 10% risk.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B

Figure 2b. Average date of occurrence of first fall frost (0°C).

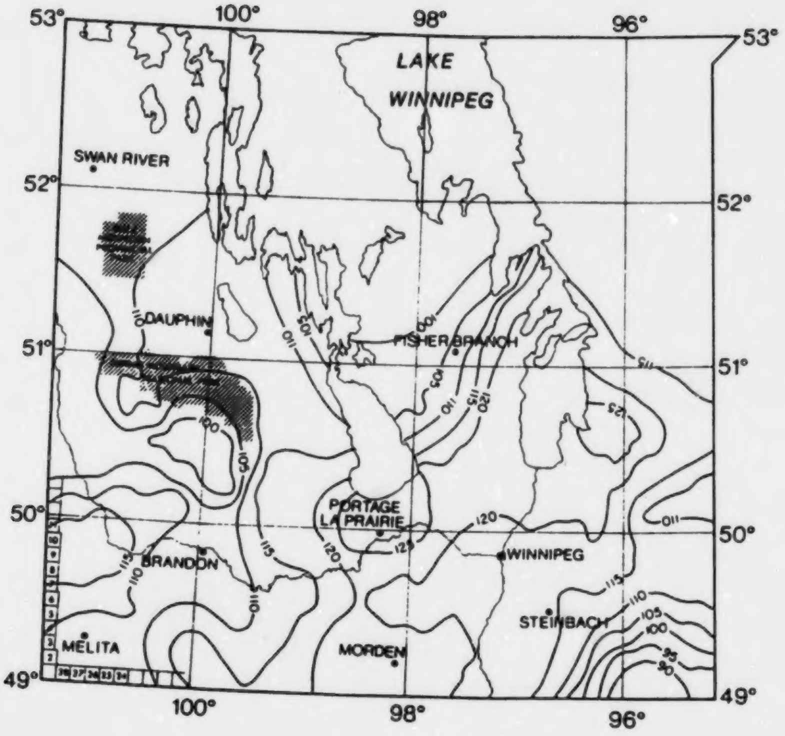
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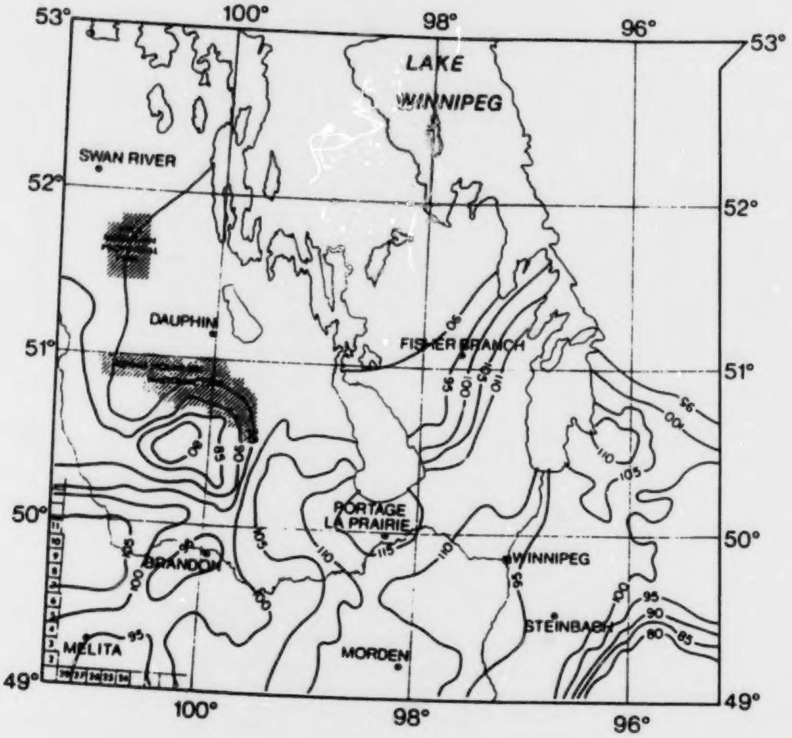
Figure 3a. Average length of frost-free period above 0°C.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B

Figure 3b. Length of frost-free period at a 25% risk. One year in four has a frost-free period of this length or shorter.

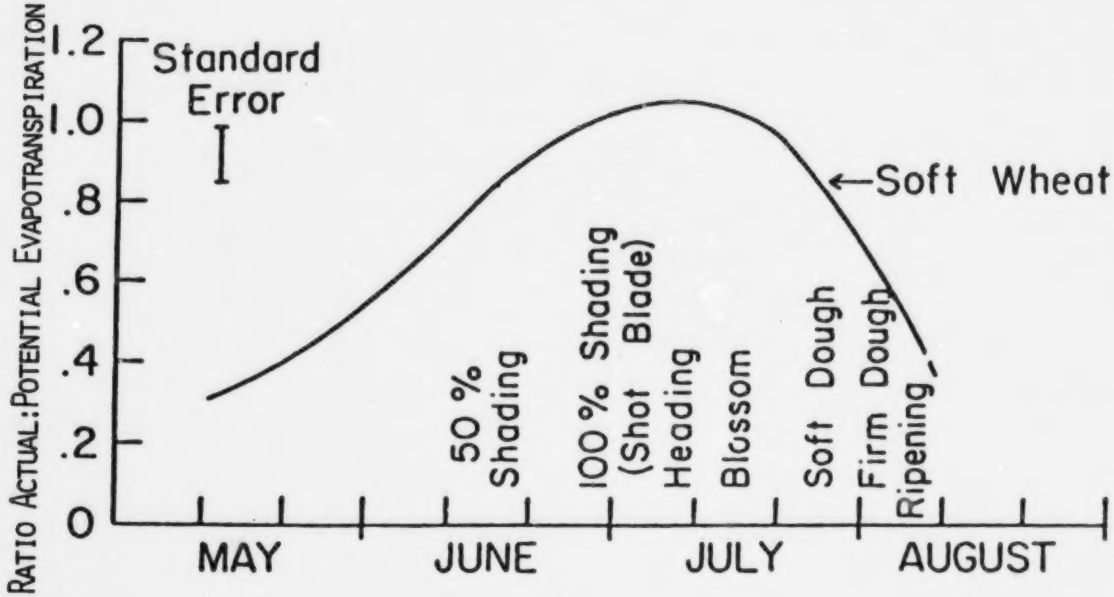


Figure 4. Ratio of actual:potential evapotranspiration for wheat as determined by Hobbs and Krogman (1968).

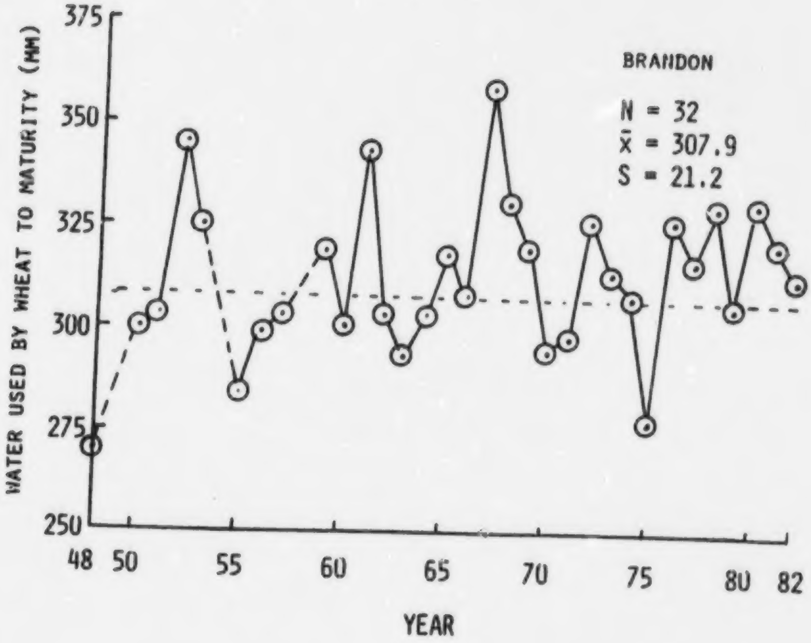


Figure 5. Estimated water use to maturity for wheat at Brandon.

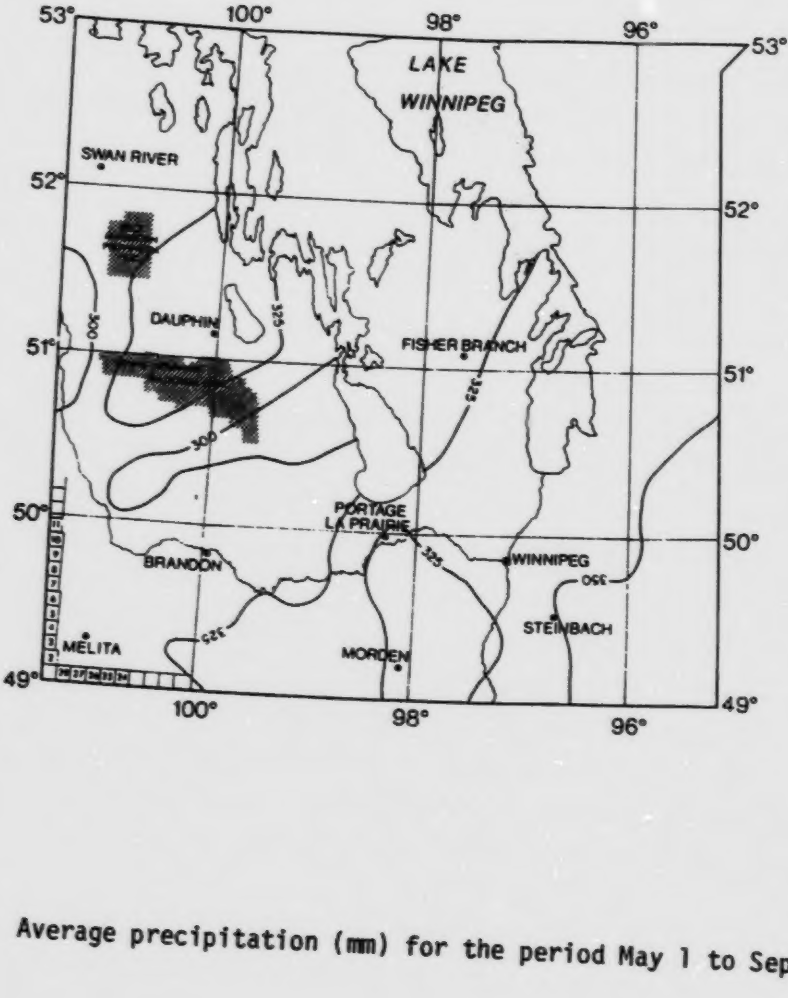
The moisture supply is the sum of the quantities (2) and (3) above. Historical data for soil moisture status at the beginning of the growing season are not available. However, by using physical models, it can be estimated from fall and winter precipitation. However, use of those models was beyond the scope of this study. Instead, the procedure assumed 100 mm of easily available water at the start of the growing season.

The other component of moisture supply is growing season precipitation. This quantity is extremely variable. A look at the average May 1 to September 30 precipitation (**Figure 6**) shows that Brandon has an average of about 315 mm. However, in 25% of the years, precipitation will be 255 mm or less (**Figure 7a**). Similarly, in 25% of the years, there will be 375 mm or more (**Figure 7b**). These data suggest wide variability in water stress on crops.

This prediction is substantiated by the estimated soil water status for Brandon (**Figure 8**). Negative numbers in the Figure indicate a water deficit. For example, a value of -100 means that the crop would have needed 100 mm more water, presumably supplied by irrigation, in order to have completed its growth without undergoing water stress. For the period 1948 to 1982, the average soil water status was -50 mm (i.e., the crop would have needed 50 mm more water to avoid water stress). However, seven years in that period had a soil water status below -100 mm. On the other hand, five years had a surplus of water (i.e., values above zero). It should be noted that a large surplus can be as detrimental to crop production as a deficit. The bottom line is that there is tremendous temporal variability in the moisture conditions under which wheat is grown at Brandon. This variability is typical of that for other locations in Manitoba and probably for the Prairies.

## 4. FALL FIELD WORKDAY PROBABILITIES

A prerequisite to fall field operations, including harvest, is that the land be tractable. This is a condition where machinery can satisfactorily move on the soil. This property is determined mainly by soil moisture status and defines the number of available "field workdays." A knowledge of field workdays and the size of the farm operation can be used as a guide to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MORDEN
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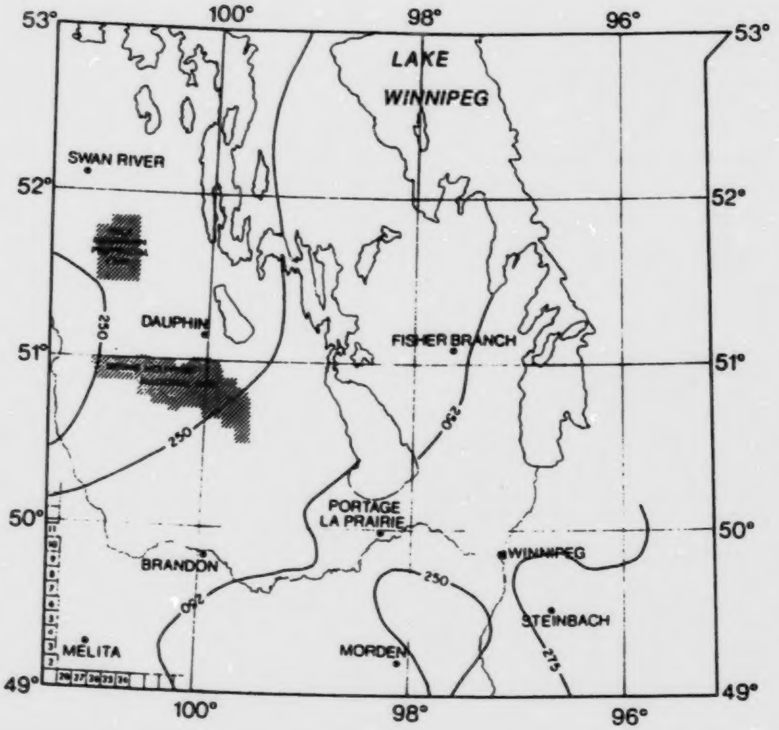
Figure 6. Average precipitation (mm) for the period May 1 to September 30.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WINNIPEG
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STEINBACH
MELITA
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275
49°
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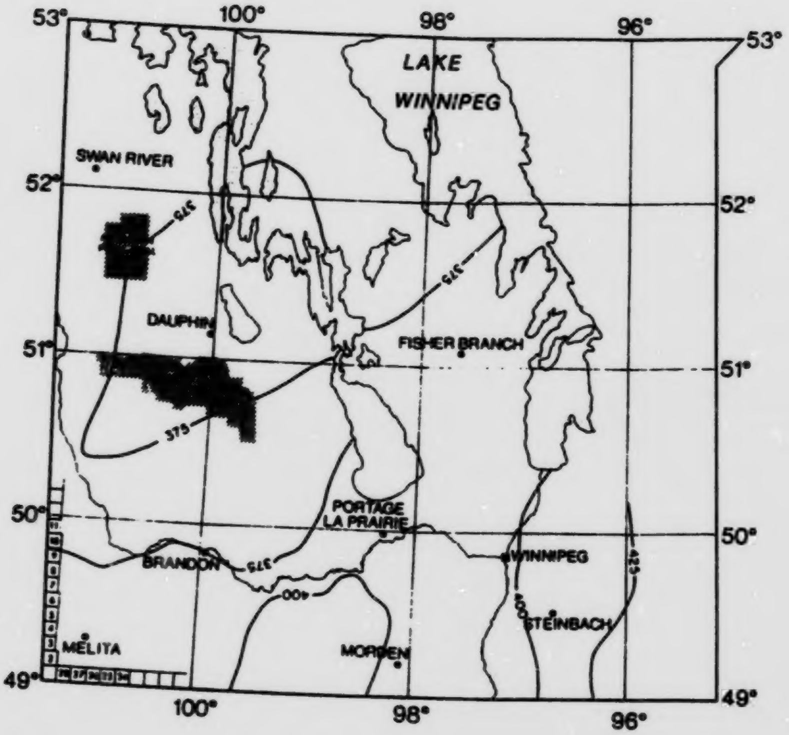
A

Figure 7a. The 25% risk map for dry years (May 1 to September 30 precipitation (mm)). Over the long term, one year in four will have this much or less precipitation.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WINNIPEG
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B

Figure 7b. The 25% risk map for wet years (May 1 to September 30 precipitation (mm)). Over the long term, one year in four will have this much or more precipitation.

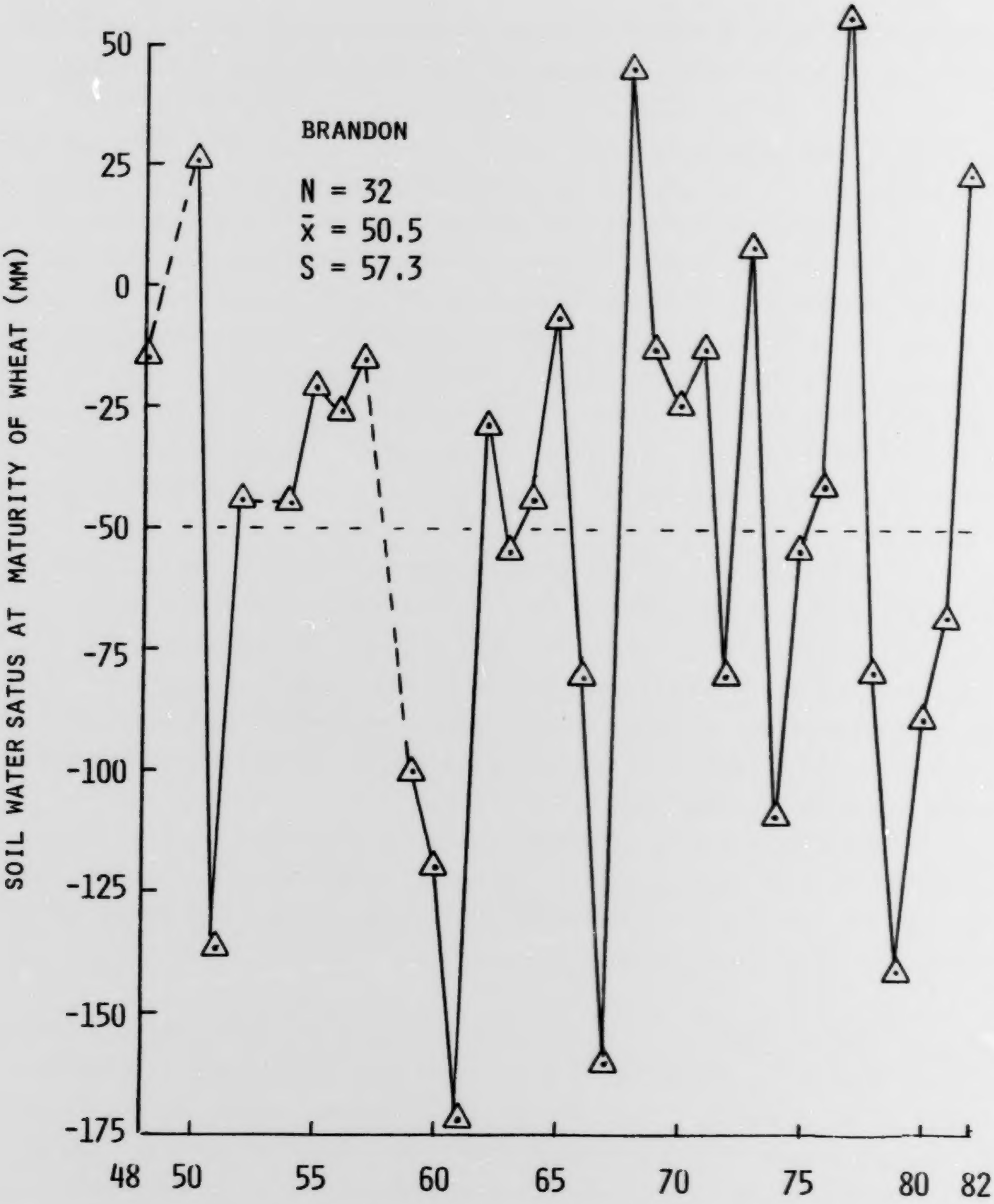

Figure 8. Estimated soil water status for wheat at maturity for Brandon. Negative values indicate a soil water deficit.

determine the size and number of pieces of machinery that a farmer should have access to. Unfortunately, the number of fall field workdays is extremely variable. For Manitoba, fall field workdays were calculated by Heinisch (1983), following the methods developed by Baier (1973), Dyer (1980), and Dyer and Baier (1979). Some of these data are presented in Table 2.

These data must be treated cautiously as they have been developed from only 18 years of weather records. However, it is clear that when the standard deviation is 20 to 25% of the mean, we are dealing with an extremely variable characteristic. Working with the data for Winnipeg and assuming that the data are roughly normally distributed, one calculates that 1 year in 6 may have 23 or less days for harvesting. By contrast, every 1 year in 6 may also have 43 or more days for harvesting. It is suggested that statistics like these make the size choice of harvesting equipment rather difficult for the farmer.

Calculations of this kind can be extremely useful. The data show that variability in the number of fall field workdays is dependent on location. Winnipeg and Brandon have about the same average number of fall field-workdays but the standard deviation is much larger for Winnipeg. Thus, the risk of a farmer not being able to harvest his crop is much higher in Winnipeg. Calculations of this kind, which assess variability, would provide useful guidelines to the farmer.

These agroclimatic parameters, although not exhaustive with respect to weather impacts on agricultural production, have served to illustrate and describe the magnitude of climate variability and its impact on biological and operational factors and systems in agriculture.

## 5. CONCLUSIONS

We are not attempting to downplay the possible impacts of climatic change on our economic, social, and political systems; rather, we are trying to increase awareness of the current effects of climate variability. Given the likelihood of an increased variability associated with any long-term climatic change, its importance in policy planning and development becomes even more critical. Once identified, a long-term climatic change allows a certain period for response and adjustment. On the other hand, climatic

Table 2. Mean and standard deviation of the number of estimated fall field workdays at selected locations in Manitoba.

| Municipality | Mean | Standard Deviation |
|---|---|---|
| Dauphin | 36.4 | 8.4 |
| Gimli | 36.2 | 5.7 |
| Winnipeg | 33.8 | 10.4 |
| Brandon | 36.9 | 6.6 |
| Morden | 40.2 | 11.7 |
| Boissevain | 40.6 | 10.5 |
| Pierson | 43.8 | 7.4 |
| Emerson | 42.4 | 10.4 |

fluctuations and anomalies are unexpected, indefensible, and potentially devastating. Frustration stems from the fact that, while we may know the nature and the extent of variability, we have no way of knowing what will occur in the coming crop year.

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# SOCIO-ECONOMIC IMPACTS OF CLIMATIC CHANGE ON PRAIRIE AGRICULTURE: THE GREENHOUSE EFFECT

by

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## ABSTRACT

A preliminary assessment is made of the socio-economic impacts of climatic change on prairie agriculture. A number of difficulties are discussed regarding the use of General Circulation Models (GCMs) as inputs to crop yield models. Four climate scenarios, based on the GCMs of the Atmospheric Environment Service, are studied. A series of models are developed to simulate the economic response to weather. These include models for the weather, seeding date, soil moisture, crop yield, and capital expenditures and economic Input-Output assessment models. The predicted yields are used to determine the economic impact of climatic change for each province.

The models suggest that the estimated economic impacts of climatic change are small; provincial crop revenue gains or losses would be felt in the trade and service sectors which are affected by the decline in farmers' discretionary expenditures.

## 1. INTRODUCTION

While climate and weather variability are important factors in planning nearly all aspects of human activity, it now appears that human activity, in turn, may affect climate. In producing heat and energy, man burns fossil fuels and thereby releases enormous quantities of carbon dioxide ($CO_2$) and particulate matter into the atmosphere. Other demands for heat, energy, and consumer goods lead man to destroy extensive areas of $CO_2$-consuming forests, thereby possibly further increasing atmospheric carbon dioxide concentrations. Whatever the cause of increasing $CO_2$ concentrations,[1] most climatologists now agree that the documented increases will bring about profound changes in climate by the next century (Shewchuck 1984). Numerous other trace gases, both naturally occurring and man made, similarly influence climate and may have an aggregate effect approaching that of $CO_2$ (Canadian Climate Centre 1985; Seidel and Keyes 1983).

The "Greenhouse Effect" generally refers to a gradual climatic warming associated with increased concentrations of $CO_2$ and trace gases. Predictions of the eventual effects of this warming trend range from more frequent droughts to a booming arctic economy, northern prairie orchards, and a U.S. midwestern desert. Of course, most of these predictions are based on pure (sometimes hopeful) speculation. Nevertheless, scientists believe that the climatic changes will be great enough that we need to develop a strategy for coping with the issue now. Possible directions for addressing the issue include adapting to the changing climate, technological control of emissions, reducing activities that emit greenhouse gases, and counteracting the effects of trace gases in the atmosphere (Seidel and Keyes 1983). The last approach is probably the least promising as it implies global weather modification procedures.

Currently, much of the research addressing the issue of climatic change has focussed on identifying the physical relationships between emission and atmospheric retention of greenhouse gases and between changing concentrations of these gases and consequent climatic effects. Because $CO_2$ represents the most important greenhouse gas, most research has concentrated on $CO_2$ emissions and concentrations.

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[1] Man's role is somewhat controversial; see Shewchuck (1984).

Considerable uncertainty still surrounds projections of expected $CO_2$ concentrations and estimates of the resulting climatic changes. However, there is sufficient scientific concern over the magnitude of current temperature increase predictions, from climatic models, that economic impact studies and policy analyses are being undertaken throughout the world (e.g., Parry 1985). These studies are currently at the stage of determining the magnitude and regional distribution of climatic impacts so that effective mitigating policies can be designed. The study described below addresses the magnitude of impacts of climatic change on the prairie agricultural sectors.

## 2. ESTIMATING THE GREENHOUSE EFFECT SCENARIOS FOR IMPACT ANALYSIS

The climatic models linking increased carbon dioxide concentrations to climatic effects are generally three-dimensional models of atmospheric circulation, so-called general circulation models (GCMs). The GCMs are selected both for their ability to explain current climate and for their relatively fine temporal and spatial resolutions (Santer 1985). The latter features are requirements for regional impact analysis. Despite the resolution advantages of GCMs, the resulting data are still usually not at a resolution sufficient to support many agricultural impact models. Temperature and precipitation predictions for this study were provided as monthly averages (although a climate inverse procedure has been developed by Wilks [1986] and others to provide daily temperature and precipitation distributions from GCM experiments). This monthly resolution is extremely fine from a climatological point of view; but crop yield models for determining economic impacts on agriculture often require daily temperature and moisture conditions, including minimum and maximum temperatures. Clearly, increased minimum temperatures early in a month that is critical to spring seeding will produce different crop yields from increased maximum temperatures later in the same month.

Similarly, agroclimatic modellers must distribute monthly precipitation changes, which are sometimes estimated to vary by nearly 100 percent from month-to-month (Figure 1), arbitrarily across the days of a month. Because

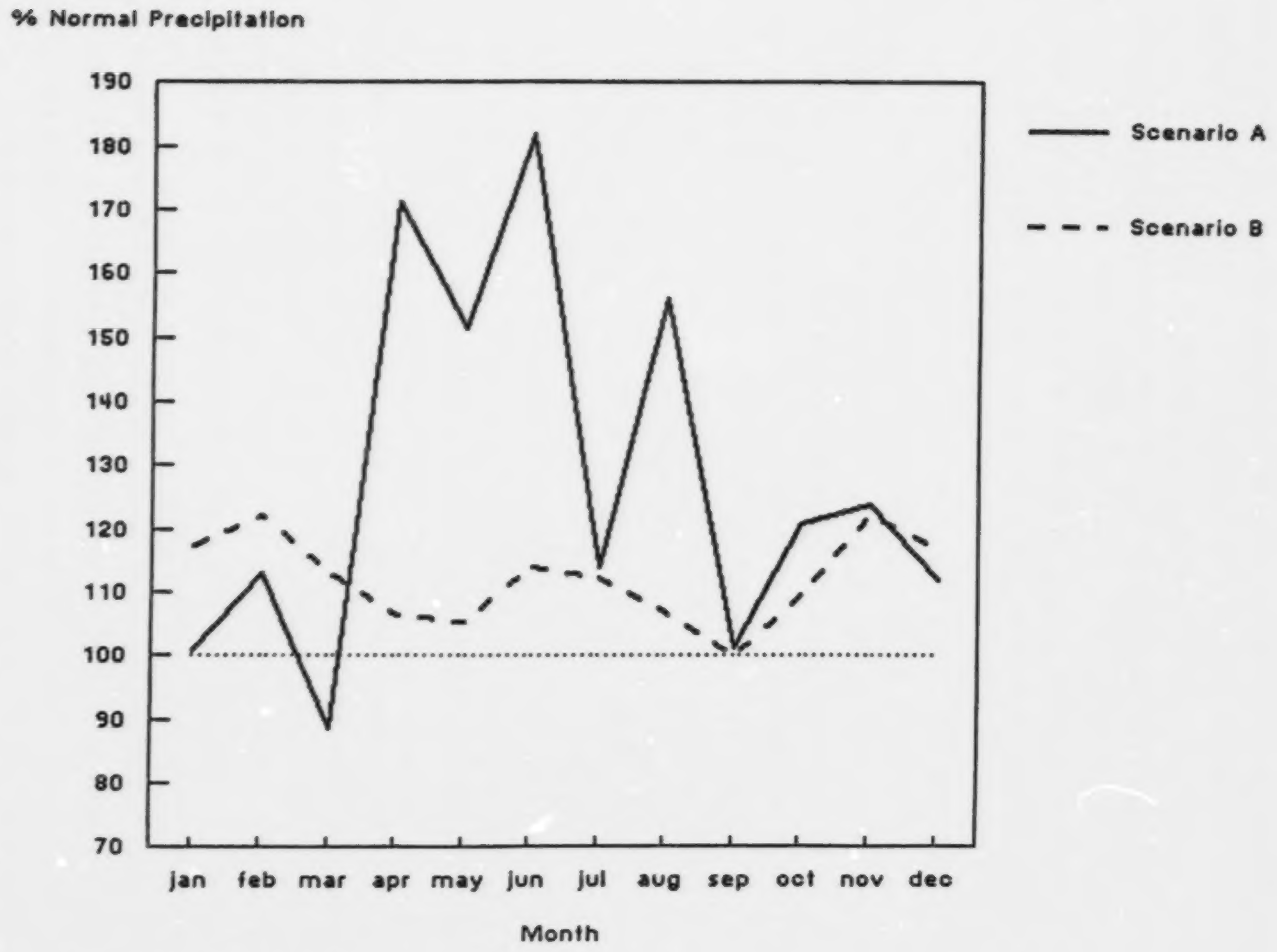

Figure 1. Precipitation changes, southern Manitoba, GCM scenarios A and B.

of these model incompatibilities, sensitivity analyses (e.g., trying different methods of distributing the temperature changes, as in this study) are often necessary elements of impact assessment (Bootsma et al. 1984).

The geographic resolution of GCM results is suitable for aggregate (e.g., national) impact analyses, but is not suitable for analysis at a regional level. The Geophysical Fluid Dynamics Laboratory (GFDL) and the Goddard Institute for Space Studies (GISS) model results used in this study, for instance, provided temperature and precipitation data for grid points ranging from 4.4 to 8 degrees latitude and from 7.5 to 10 degrees longitude.[2] Temperature and precipitation estimates can vary dramatically across neighboring grid points (e.g., by over 100 percent for precipitation), and, thus, various arbitrary distributions between grid points produce very different results. Greater density of weather recording stations, particularly for precipitation events which can be extremely localized, is likely necessary before geographic resolution can be improved (Wilks 1986).

The errors of GCMs for 1 x $CO_2$ (current concentrations) have been estimated at a factor of 2 for precipitation and up to $5^{o}C$ for temperature. Thus, small temperature changes under a hypothetical $CO_2$ scenario (e.g., 2 x $CO_2$) become difficult to evaluate. Again, sensitivity analysis, such as use of temperature changes from various GCMs, becomes necessary. In the case study discussed below, several variations in temperature and precipitation are used.

A further problem with GCM-generated climatic scenarios is that they give changes in long-term normal conditions but provide no indication of the distribution of the changes over time. Thus, questions remain concerning expected changes in the variability of weather. As we have heard in previous presentations, weather variability is as important a constraint to prairie agriculture as long-term average climate.

Despite these and other difficulties in determining the economic impacts of climatic change using currently available scenarios, such impact studies provide general indicators of the magnitude and direction of expected effects.

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[2] The distance is approximately 300 to 550 miles north to south and 400 to 500 miles east to west.

## 3. CASE STUDY: EFFECTS OF CLIMATIC CHANGE ON PRAIRIE AGRICULTURE

### 3.1 THE CLIMATIC CHANGE SCENARIOS

Two climatic scenarios were provided by the Atmospheric Environment Service (AES), Environment Canada, based on GCM experiments undertaken using the GFDL and GISS models. For Scenario A, 4 x $CO_2$ experiments were divided by two to obtain temperature and precipitation changes for grid points of 4.4 degrees latitude by 7.5 degrees longitude. For Scenario B, 2 x $CO_2$ experiments were run for a network of 8 degrees latitude by 10 degrees longitude, though interpolations were made to 4.0 degrees latitude by 5.0 degrees longitude. AES compared these results to similar experiments for 1 x $CO_2$ (i.e., simulated normal baseline conditions) to derive changes in monthly temperature and precipitation (Table 1). These average monthly changes were then added to historic, daily weather data for each year from 1961 to 1985, using either a flat distribution (referred to as Scenario A and B) or a trigonometric distribution as in Brooks (1943) (Scenarios A2 and B2). Economic and agronomic effects of these climatic change scenarios were compared to simulated effects of long-term average weather (1961 to 1985 average weather used as the "baseline") and of a major historic drought. Weather from 1961 was used for the latter scenario, as it caused the most severe and widespread agricultural drought in recent record.

### 3.2 METHODS

A series of models were developed to simulate economic responses to weather. The models are primarily deterministic and the linkages among models unidirectional (Figure 2). The series begins with weather models, which translate the monthly long-term averages of the climatic change scenarios into daily temperatures and moisture at the numerous prairie weather stations.

Biometeorological time scales (BMTS) were developed for various prairie crops, over the period 1961 to 1985, based on day length, daily temperature, and historic seeding dates. These scales were used to calculate

Table 1. Descriptive statistics of climatic change scenarios.

| | Scenario | | | |
|---|---|---|---|---|
| | A | | B | |
| | Southern Manitoba | Northern Alberta[a] | Southern Manitoba | Northern Alberta[b] |
| Temperature Change (+C)[c] | | | | |
| Average (annual) | 2.57 | 2.79 | 4.58 | 4.64 |
| Standard Dev. | 1.44 | 1.46 | 0.96 | 1.06 |
| Low (month) | 0.40 (July) | 1.20 (Feb., Nov.) | 3.10 (July) | 3.30 (June, July) |
| High (month) | 6.00 (April) | 6.10 (April) | 5.70 (Jan., Dec.) | 6.20 (Jan., Dec.) |
| Precipitation Change (% normal)[c] | | | | |
| Average (annual) | 128.07 | 114.85 | 113.87 | 122.14 |
| Standard Dev. | 28.62 | 28.75 | 8.09 | 11.58 |
| Low (month) | 88.80 (Mar.) | 72.40 (June) | 95.80 (Sept.) | 100.00 (Sept.) |
| High (month) | 171.50 (Apr.) | 196.80 (Sept.) | 123.50 (Jan., Dec.) | 141.20 (Jan.) |

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[a] Approximately Peace River region.

[b] Approximately Edmonton region.

[c] Change from 1 x $CO_2$ experiments.

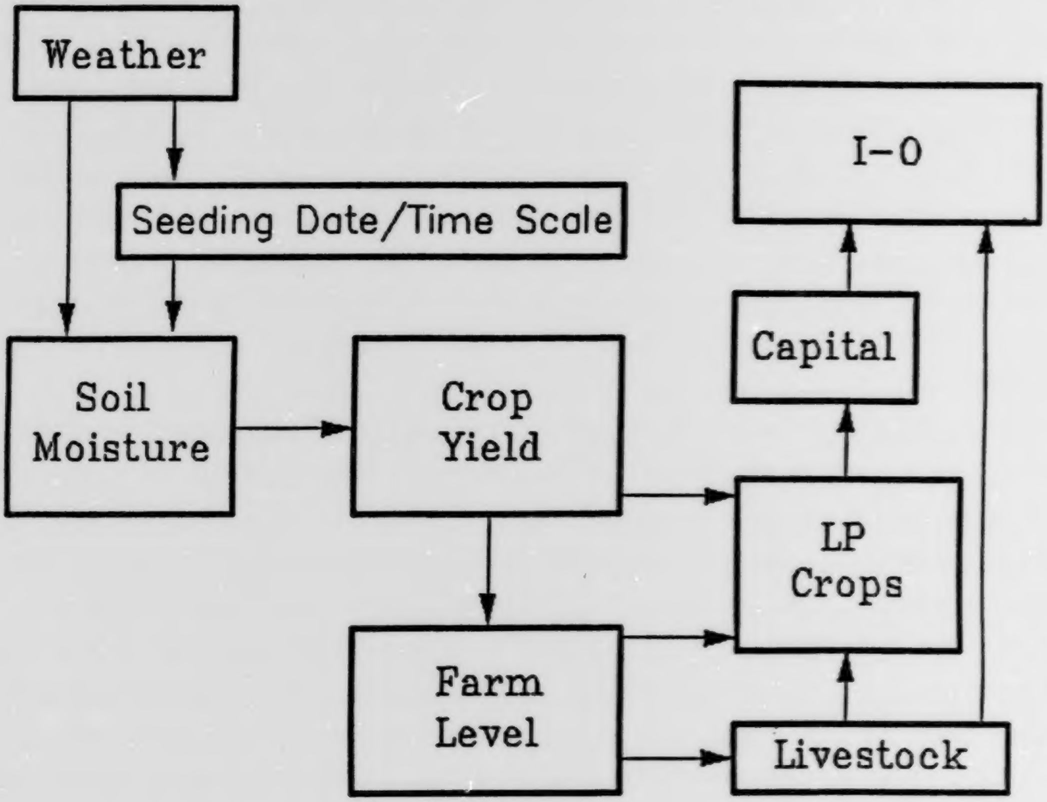

Weather
Seeding Date/Time Scale
Soil Moisture
Crop Yield
Farm Level
I-O
Capital
LP Crops
Livestock

Figure 2. Model flows.

a crop's daily progress toward maturity under various weather conditions. In order to simulate artificial weather scenarios, an algorithm was developed to endogenize the seeding decision (seeding date) and, by extension, the time scales for both historic and simulated (scenario) weather. The algorithm uses only climatological data to determine the feasibility of seeding. Due to increased temperatures (and reduced risk of frost) under Scenarios A and B, the simulated seeding dates are generally earlier than the historic dates. Occasional delays in seeding do occur under scenarios that include precipitation increases. On average, spring seeding occurs only one to three days earlier under the latter scenarios because, in some years and on some soils, increased precipitation delays access to fields. While early seeding does not necessarily result in a corresponding early harvest (due to the short daylight hours during early spring), crops do tend to mature earlier under the changed climate.

Results from the BMTS model, using revised seeding and growth stage dates, were used in the Versatile Soil Moisture Budget (VSMB) model to estimate soil moisture stresses by crop, seedbed (stubble, fallow, and reduced tillage stubble), crop growth stage, soil texture (holding 125 to 150, 200 to 225, or greater than 280 mm of available moisture), location, and weather year. The VSMB model, obtained from Agriculture Canada for each prairie crop reporting district (CRD), estimates soil moisture as a function of potential evapotranspiration, crop rooting pattern, available soil moisture, and soil moisture release characteristics (Baier et al. 1979). The model simulates daily conditions throughout the year. It takes into account precipitation and runoff as well as snow accumulation and snow melt.

Moisture shortfalls are defined in terms of the difference between available moisture and required moisture for each crop for each defined growth stage. An aggregate soil moisture deficit for each crop growth stage in each CRD is calculated by taking a weighted average of deficits on the various soil textures, based on the proportions of each texture in each CRD.

### 3.2.1 Yield Models

Soil moisture deficits represent only one of many factors that influence crop yields. Examples of other factors include fertilizer use, extreme weather events such as frosts and floods, pest problems, and variety selection. The crop yield models quantify most of these relationships, via regression equations expressed in translog functional form. The translog variation on the moisture stress variables allows yields to both increase and decrease with increases in soil moisture, depending on the actual level of moisture.

The yield responses quantified in the regression models account for only the temperature and moisture changes due to doubled $CO_2$ concentrations. Increased $CO_2$ has also been shown to affect a crop's water use efficiency, particularly for horticultural crops in greenhouse conditions (Kimball 1982). However, yield increases (in the absence of the climatic effects of increased $CO_2$) in average field conditions are extremely uncertain and were not included in the yield estimates.

Equations that estimate yield have been derived for 20 crop subdistricts and 5 major crops (wheat, oats, barley, canola, and flax) in Saskatchewan, for 12 CRDs and 12 major crops (the 5 from Saskatchewan plus winter wheat, rye, grain, and silage corn, sunflowers, tame hay, and native pasture, as well as some grains under reduced tillage techniques) in Manitoba, and for grains and oilseeds in 8 subdistricts of Alberta. Separate equations were developed for stubble and fallow seedbeds and for reduced tillage.

All of the yield models show statistically significant goodness of fit; most models show significant yield responses to moisture. Exceptions are found in some of the models for canola, for which a much smaller data set was used. This is due to its recent and geographically limited adoption. The models also show a yield response to improved technology over time. Therefore, the "predicted" yields used for this study reflect response to moisture only, with technology held at the 1980s level (Figure 3).

### 3.2.2 Economic Models

The predicted yields for each scenario were used to determine economic impacts of climatic change in each province. For Manitoba, the yields were entered into a linear programming (LP) model. Given physical, biological, and economic constraints on the sector, the model used expected yields to adjust CRD cropping patterns to maximize net crop revenues. The

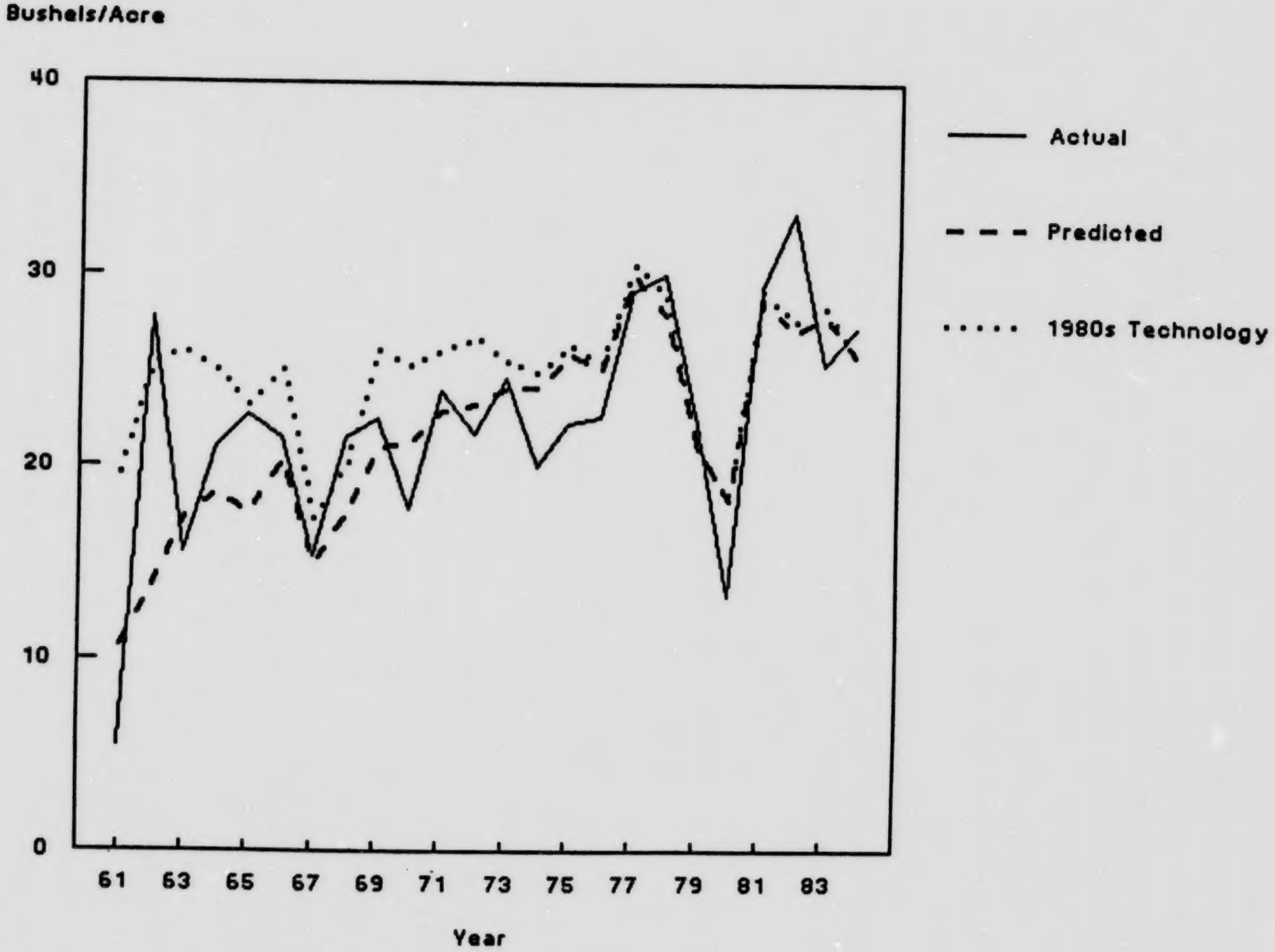


Figure 3. Stubble seeded spring wheat yields in CRD 1.

Manitoba crop revenues, expenditures, and household farm incomes simulated by the LP model were used as inputs to an Input-Output (I-0) model of non-agricultural sectors of the Manitoba economy. This I-0 model was used to determine scenario effects on agriculturally linked sectors of the economy.

For Alberta and Saskatchewan, economic impacts on the agricultural sectors were extrapolated from summations of the yield effects multiplied by current (1985 to 1986) crop prices. The Prairie Farm Rehabilitation Administration (PFRA) (Kulshreshtha and Yap 1985) provided I-0 models for these provinces, which were used to determine impacts on nonagricultural sectors.

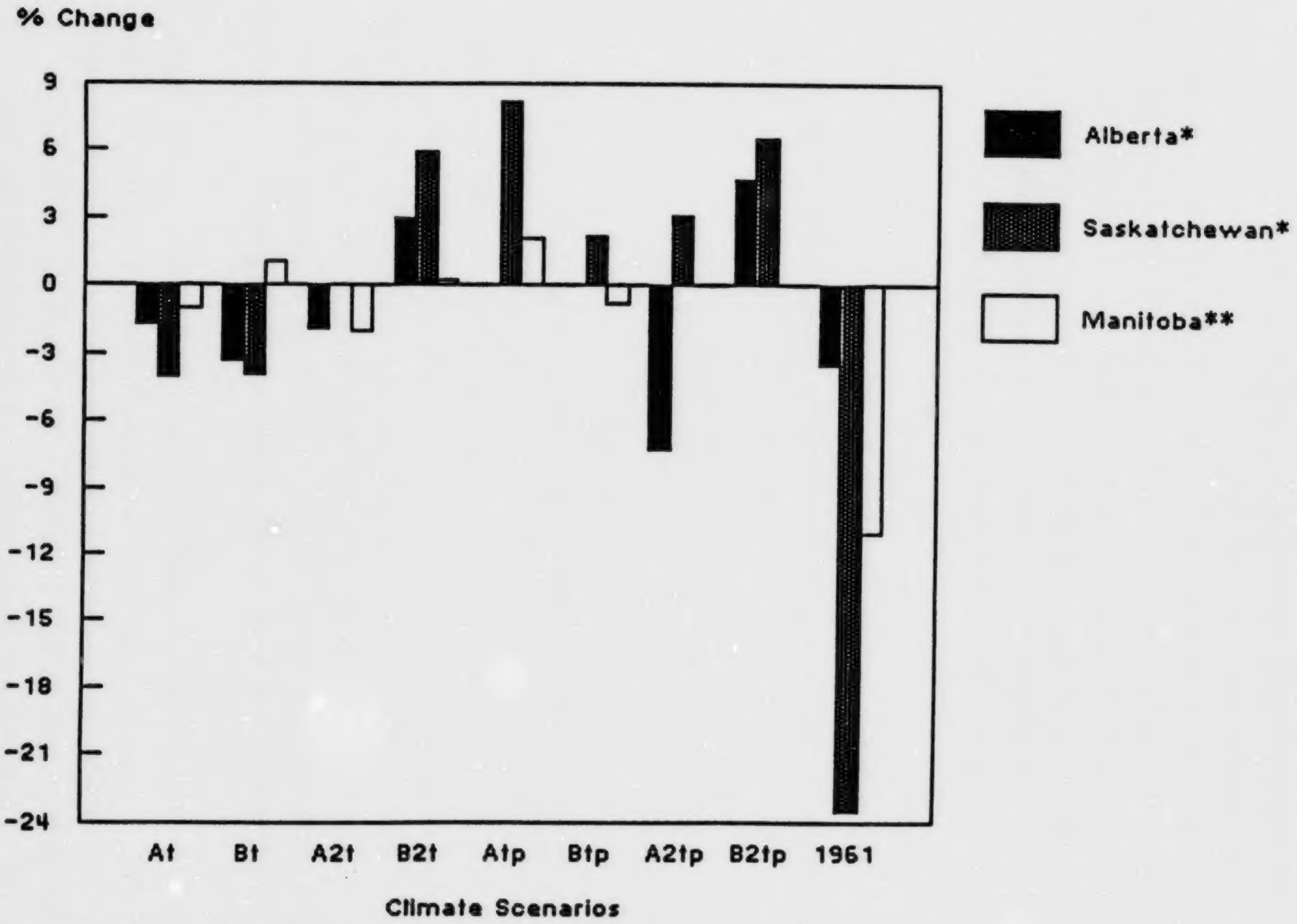
## 3.3 RESULTS AND DISCUSSION

The pattern of results varies dramatically across crops, regions, baseline years, and scenarios; generalization is difficult. Therefore, only aggregate economic results are discussed.

### 3.3.1 Agriculture

While temperatures rise under all climatic change scenarios, in some prairie regions the increases are small during the growing season (e.g., 0.8°C in June and 0.4°C in July for Scenario A in central and southern Saskatchewan). In these areas, a slight increase in precipitation can offset increases in evapotranspiration. Earlier seeding, due to a 6.4°C increase in April in the same scenario and region, can result in a new crop growth time scale relative to historic patterns. This would enhance production volumes. The increases in production in these regions would often be offset by decreases in other regions (or vice versa), resulting in reduced province-wide effects.

Therefore, most of the estimated economic impacts of climatic change are small; provincial crop revenue gains or losses generally range from one to eight percent (Figure 4). The greatest impacts include: (1) a seven percent revenue decrease under scenario A2 in Alberta; (2) a five to seven percent increase under B2 in Alberta and Saskatchewan; and (3) an eight percent increase under both A conditions in Saskatchewan. The Saskatchewan and



* Wheat, barley, and canola
** All crops

Figure 4. Percentage change in crop receipts by scenario.

Alberta results do not allow for adjustments in cropping patterns, partially explaining the larger magnitude of effects in these provinces.

The impacts of long-term climatic warming do not approach the magnitude of a 1961-type drought. The drought of 1961 caused an 11 percent crop revenue loss in Manitoba, a 24 percent loss in Saskatchewan, and a 4 percent loss in Alberta.[3] Increased frequencies of major droughts under climate change represent a greater threat than the long-term increase in temperatures per se. Unfortunately, it is not known what the changes in frequencies of such drought events will be under the Greenhouse Effect.

### 3.3.2 Other Sectors

Economic effects on other sectors of the provincial economies, as modelled in I-O models, are related to changes in the farm sectors' expenditures for farm inputs and consumer goods and services. While on-farm expenditures remain fairly constant across climatic scenarios, discretionary expenditures of households and enterprises (e.g., farm equipment) change in response to changing cash flows. For example, if there is a long-term, net revenue decline in the Manitoba agricultural sector, production activities in sectors servicing agriculture will decline as well. In aggregate, the declines will be nearly proportional to the original decline in the agricultural sector. For instance, under continuing droughts, output and employment could be expected to decline in all sectors except feed manufacturing (more feed supplements will be purchased). The greatest losses would be felt in the trade and service sectors which are affected by declines in farmers' discretionary expenditure (Arthur and Freshwater 1986).

### 3.3.3 Northern Expansion

While considerable area is available for farming north of the currently arable zones of the prairies, much of the land is only marginally suitable for farming, even under the increased temperatures of Scenarios A and

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[3] The 1961 drought was not as severe in some regions of Alberta.

B. Although 3.1 million hectares of organic soils are estimated to become available under Scenario A, the forages that could be grown on these soils would not generate sufficient net returns to warrant production, much less development of a new agricultural infrastructure, in the current (or even anticipated) economic environment. Similarly, much of the four million hectares of mineral soils would be suitable only for forage production.

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# CLIMATOLOGICAL STUDIES IN ALBERTA

by

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## ABSTRACT

The findings of a major climate research review are highlighted. The climate research review spans the time from 1975 to 1986 and contains over 300 bibliographic references of climatological studies in Alberta.

Individual areas of Alberta have received considerable attention from scientists working in the field of environmental climatology. Descriptive climatologies have been published for southern Alberta, the mountain regions, the oil sands area, Calgary, and Edmonton. Research in physical climatology has focussed on understanding the precipitation processes of hail, rain, and snow formation, lightning, chinooks, and tornados.

There has been significant research in the fields of agriculture, forestry, and hydrology. Conversely, areas of tourism and recreation, building design, construction, and transportation have received little research attention and have made limited use of available climate data in the planning process.

Major research recommendations relate to the quantification of relationships, both direct and indirect, between climate and the resource sectors. The constraints and incentives that influence how society responds to climatic variability must be identified. Four priority research areas are presented.

# ACKNOWLEDGMENT

The authors wish to acknowledge, with thanks, the valuable assistance of our colleagues Mike Brennand and Bob Myrick. Their writing and organizational skills were appreciated. Thanks are also extended to the numerous authors, who through discussions and their publications, helped to compile the bibliography.

## 1. INTRODUCTION

"Drought feared in southern Alberta." One would think this was a headline from the past, probably 1985; but it is not. This is a headline from the Edmonton Journal of 1987 June 12. Other headlines read "Dry spell has farmers in suspense" and "Dry weather compounding Alberta farm problems." Once again, the farmers of southern Alberta scan the horizon. They watch fearfully for grasshoppers and eagerly for rain clouds. This year, however, the farmers can smile. A recent headline from 1987 July 07 reads "Timely rain welcome break for farmers." Other industries, such as forestry and transportation, are also affected by weather events. Climate variability and potential climatic change are facts of life for Prairie residents. Mild, virtually snow-free winters followed by May snowstorms have contributed to the heightened public awareness of climate issues.

Apparent worldwide climatic changes and increased variability are receiving more and more attention. Large projects such as the World Climate Research Program (WCRP) and the Canada Climate Program (CCP) exist to understand climate and climatic change processes (Ferguson and Phillips 1986). The effects of $CO_2$ and other trace gases have been intensely studied in recent years in order to understand their impacts on climate. The review of all literature on climatic variability and change, however, is beyond the scope of this report.

The main purpose of this paper is to highlight the findings of a major research review of climatological studies in Alberta which is currently being completed. Climate and climate-related research in Alberta have been summarized in the review. Reports or articles published primarily between 1975 and 1986 were reviewed to extract the purpose, conclusion, and research recommendations. Earlier studies were included only if they were part of a series of work by an individual author or if no other similar work had been done. The bibliography was developed through computerized literature searches and personal contact with researchers and managers. To date, over 300 bibliographic references have been compiled.

The references discussed here emphasize areas of significant research and areas where little research has been completed. The final report will be of benefit to researchers, students, resource managers, planners, and the public who are involved in areas of environmental concern. It will undergo a lengthy review process and, accordingly, the recommendations presented at this time are tentative. Additional recommendations may develop from the workshops held at this Symposium.

Before embarking on this review, the boundaries or parameters were set. What do we mean by "climate" as opposed to "weather"? "Climate" can be broadly defined as the summary conditions of the atmosphere at a given time. This is described through average statistics as well as extremes, frequencies, and probabilities. "Weather" pertains to the instantaneous description of the atmosphere in terms of the physics and dynamics responsible for its present state.

## 2. THE CLIMATE OF ALBERTA AND ITS REGIONS

Studies of the year-round climate of a particular region are referred to as "descriptive climatologies". The most thorough assessment of the climate of Alberta was completed by the leading climatologist, the late Richmond Longley (Longley 1972). Alberta can be described as having a continental climate, subject to extremes in temperature and precipitation. The year can be divided into two primary seasons: a short, cool summer and a long, cold winter. These are separated by short, transitional seasons - spring and autumn.

Individual regions of Alberta have received considerable attention (Figure 1). Descriptive climatologies have been published for southern Alberta (Fletcher 1972), the mountain regions (Cote 1984; Janz and Storr 1977), and the oil sands area (Leahey and Hansen 1982; Longley and Janz 1979; Rudolph et al. 1984). Two larger reports have been devoted to the climates of Calgary (Klivokiotis and Thomson 1987) and Edmonton (Olson 1985).

The application of climate information to park management is a theme common to both The Climate of the Contiguous Mountain Parks (Janz and Storr 1977) and The Climate of Kananaskis (Cote 1984). Data were assembled to establish climatological principles for the park, which can have important implications for park management. Janz and Storr (1977) provide a checklist of important climate elements to be considered in planning park facilities. These authors recommend that long-term records and stations be maintained in a

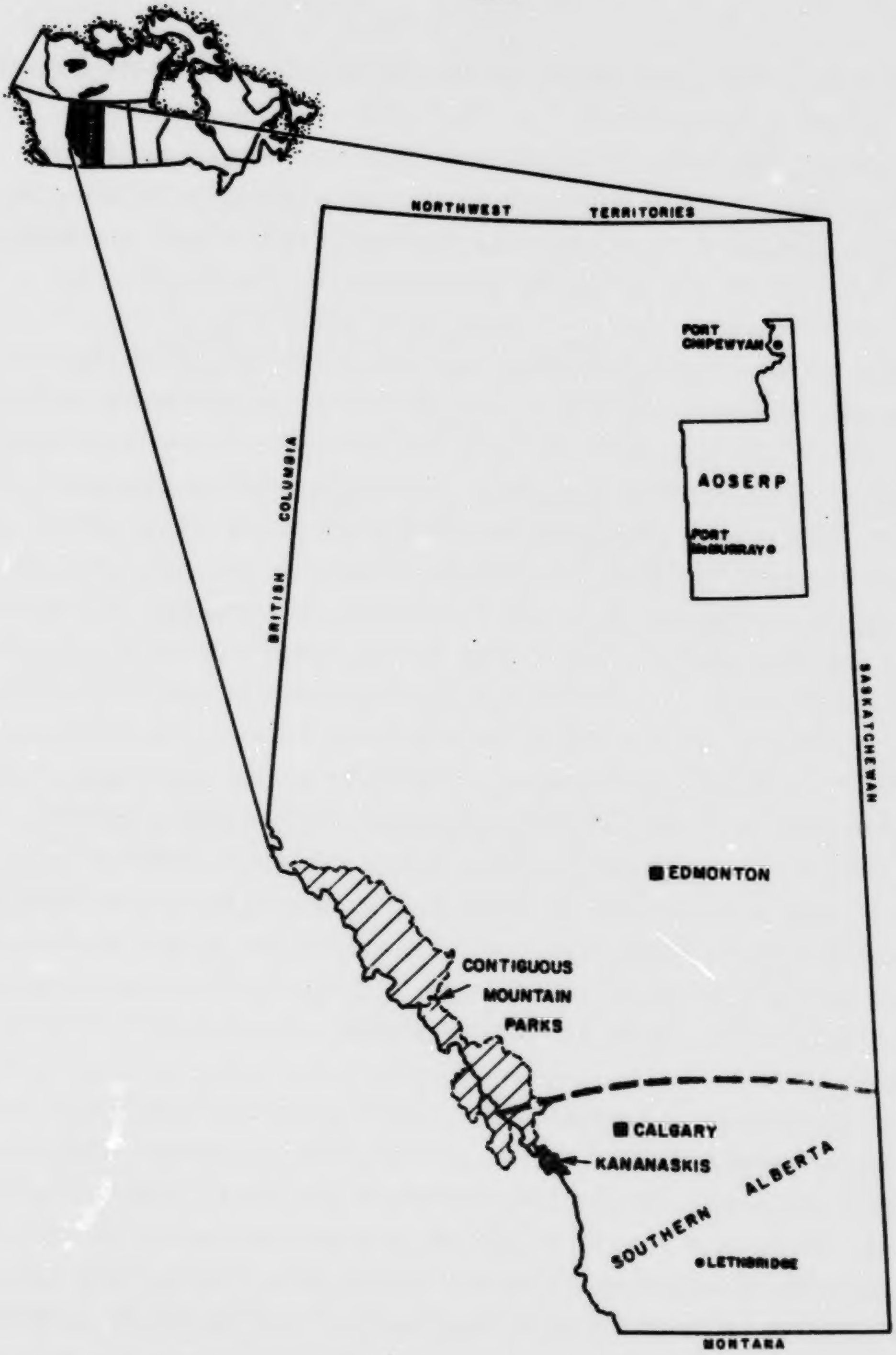
NORTHWEST TERRITORIES
FORT CHIPEWYAN
AOSERP
FORT McMURRAY
BRITISH COLUMBIA
SASKATCHEWAN
EDMONTON
CONTIGUOUS MOUNTAIN PARKS
CALGARY
KANANASKIS
SOUTHERN ALBERTA
LETHBRIDGE
MONTANA

Figure 1. Special areas of climatological studies in Alberta.

variety of topographical settings to adequately describe the volatile mountain climates; automatic recording stations are suggested. The Climate of Kananaskis (Cote 1984) was predicated on meeting the needs of public and private concerns in terms of assessing Kananaskis' climate for future cultural developments. This area is particularly important for outdoor recreation. Cote also promotes the use of climate information in site selection for recreational activities.

The advent of industrial development in northeast Alberta spurred the climatological studies of the Alberta Oil Sands Environmental Research Program (AOSERP). Due to the oil sands and heavy oil developments, air quality is a major concern in the region. The climate studies focussed on inversion frequencies, wind speeds and direction, and the effects of topography on winds (Leahey and Hansen 1982). The only climate stations in the area are Fort McMurray and Fort Chipewyan which are separated by approximately 220 km. Their data are inadequate to describe the total climate picture. In particular, Longley and Janz (1979) strongly urged that more wind data be collected for the region, especially for modelling purposes. Rudolph et al. (1984) completed the last assessment of climate in the oil sands area. This study incorporated data from newly installed automatic weather stations, forestry service towers, Atmospheric Environment Service Fort McMurray records, and some minisonde data. A number of recommendations were made; in particular that future studies begin with an examination of data quality and the intent or objective of the measurements. It is suggested that a future study attempt to relate frost-free periods at the automated stations to Fort McMurray data.

The climate of Calgary and Edmonton are described in detail in two Atmospheric Environment Service reports (Klivokiotis and Thomson 1987; Olson 1985). These are good, complete descriptions of the cities' climates. They also discuss the applied aspects of climate data such as recreation or gardening. These reports present the most recent assessment of long-term data. Each season is described under headings such as temperature, precipitation, clouds, relative humidity, and winds. Edmonton is distinguished by the extreme variability of its climate. It is noted that rapid urbanization in

Calgary has raised the city's annual temperatures from 3°C to 9°C above those in the suburbs.

The purpose of these descriptive climatologies was to summarize data. Short-term data sets are related to the long-term normals, allowing the comparison of sites. Few recommendations for further studies were made.

## 3. PROGRESS IN PHYSICAL CLIMATOLOGY

Research of a more theoretical nature, dealing with the physical processes of the atmosphere such as heat or moisture exchange, has been grouped together under the topic of physical climatology. This includes the spatial and temporal variations of these parameters. These variations may be due to local topography, geographical location, altitude, latitude, mountain barriers, water bodies, prevailing wind, and the synoptic climatology. In Alberta, this research has concentrated on a limited number of topics including precipitation processes of hail, rain, and snow formation, lightning, and chinooks.

### 3.1 RAIN

Climatologies describing the spatial and temporal variations in precipitation have been completed for the whole province and for the Eastern Slopes (Longley 1972; Janz 1977; Laycock 1978; Nkemdirim and Weber 1976; Powell 1977; and Reinelt 1970). According to Reinelt, orographic uplift contributes up to 37% of mountain rainfall. This decreases to 13% in the plains where convective processes dominate. Powell concluded that short-term meteorological networks should be incorporated into the climatological data base so that a more accurate precipitation climatology for the mountain regions may be achieved. Nkemdirim and Weber studied sequences of wet and dry years in Alberta. It was found that precipitation in Alberta is largely controlled by air mass movement and frontal passages. The highest annual precipitation variability was found in the mountain regions; the greatest consistency in precipitation was in the central portions of Alberta.

Research conducted by the Alberta Research Council has concentrated on rainfall of a more convective nature. The utility of using weather radar as an indication of spatial and temporal precipitation distributions has also been addressed. Data collected since 1975 have been used to derive intensity-duration curves within a 150 km radius of the radar location at Penhold. The greatest application of this technology to date is in the hydrological field of flood forecasting.

## 3.2 SNOW

Snow climatology research in Alberta has been limited to the southwestern portion of the province. In 1982, the Alberta Research Council initiated a project designed to develop a snow climatology of the southern Alberta Rocky Mountains. Its purpose was to assess the potential for augmenting snowfall through cloud seeding. Barlow et al. (1983) studied snow climatology from temporal, spatial, and altitudinal perspectives using a 29-year data base consisting of a variety of snow measurement networks. This work was followed by Thyer et al. (1985) who described snowfall characteris tics, snowfall and upper air relationships, and snowfall-snowpack relationships.

By applying and building on the earlier snow climatologies, Barlow et al. (1986) developed a climatology of orographic cloud microphysical characteristics. These authors confirmed that orographic clouds contain large amounts of liquid water which can potentially be transformed into precipitation.

## 3.3 HAIL

Alberta has been the location of some of the most extensive hail research in Canada and the world. Central Alberta has one of the highest frequencies of hail occurrence in the world (Summers and Wojtiw 1971). Property damage due to hail can be significant. Wojtiw (1986b) reported that hail damage resulting in crop losses has totalled over 100 million dollars per year. Makowsky (1982) reported 98 million dollars in property damage and 3.1 million dollars crop damage caused by one evening of intense hail activity in and around the city of Calgary. Recently, the property damage estimates following Edmonton's hail and tornado event of 31 July 1987 are close to 300 million dollars.

Hail research has focussed on both the climatology of the storms and the application of climatology to the physical and microphysical characteristics of hailstone growth. The spatial, temporal, and seasonal variation in hailfall and hailstorm characteristics have been extensively explored by Wojtiw (1975, 1977, 1979, 1981, 1986a,b). Makowsky (1982) suggested that, if more climatological work was done to understand severe storms, recommendations could be made as to the prediction, preparation for, and even modification of such events.

## 3.4 LIGHTNING

The climatological significance of lightning is of great importance to the forestry industry in Alberta. Lightning strikes are one of the major causes of forest fires. A lightning system consisting of seven directional finders, a central position analyzer, and a remote display processor has been set up throughout the province by the Alberta Forest Service. The purpose of this network is to assess the climatatology of thunderstorms, and in particular lightning strikes. Nimchuk and Janz (1983), of the Alberta Forest Service, reported that two types of lightning are common in Alberta. Positive lightning, where the charge is transferred from the ground to the cloud base, is common in Alberta. It is more likely to cause forest fire starts than is negative lightning, where charges are transferred from the cloud to the ground. Positive lightning is more common in mid and northern latitudes because of the cooler nature of the clouds. In Alberta, positive lightning is common and is more frequent with cooler weather (late fall). Nimchuk and Janz emphasize that lightning strikes are likely much more frequent and evident from smaller convective clouds than the literature states due to the sparseness of the lightning network. Much of the dry lightning strikes of northern Alberta are thought to be positive in nature.

## 3.5 TORNADOES

Tornadoes have been studied climatologically by Hage (1977). This climatological study was based on local histories, newspapers or taped interviews. Although highly infrequent, tornadoes can and do occur. Hage reported that most tornado observations are in southern and central Alberta. Due to a lack of numerical data, Hage's theoretical equations relating to storm path dimensions are unverified. Hage's work continues with data from the recent tornado in Edmonton in July 1987.

### 3.6 CHINOOKS

Many people would consider chinooks to be the most important meteorological phenomena to occur in Alberta. There are a number of definitions of chinook in the literature, illustrating the difficulty in determining an all-encompassing definition. The significant meteorological factors commonly used to describe a chinook include maximum winter temperatures exceeding 4.4$^{\circ}$C (40$^{\circ}$F), and a wind direction of SSW to NNW at speeds greater than 4.5 m/s at the measurement site.

Most published studies on chinooks have been descriptive (e.g., Ashwell 1968; Danielewicz 1977; Lester 1975, 1976; Longley 1969). Forecasting is presently the major research focus. Drews (1981) contends that an accurately forecasted warming trend due to a chinook could prove beneficial to street maintenance and snow removal costs, ventilation of urban air pollutants, and even the physiological well-being of Albertans. However, chinook dynamics remain poorly understood and require more research.

## 4. PROGRESS IN APPLIED CLIMATOLOGY

The recent catastrophic experiences in Edmonton and around the province have shown how costly severe storms can be. The price tag includes not only the cost of reconstruction, but also the cost of lost resources and jobs. Climate variability can have tremendous environmental and socioeconomic impacts. Consider for a moment, what effect a 1$^{\circ}$C mean annual temperature increase would have on the agriculture industry in Alberta. The answer is at best an estimate.

There have been few impact studies completed in Alberta. Decisionmakers are hindered in their consideration of climatic variables because they lack detailed cost-benefit analyses in a number of economic sectors. It is essential to know not only the primary response of the natural system but also the interactive relations between climatic variables and socio-economic activities (Sewell and MacDonald-McGee 1983).

## 4.1 AREAS OF SIGNIFICANT RESEARCH

There has been significant applied climatological research in three economic sectors: agriculture, forestry, and hydrology.

### 4.1.1 Agriculture

The climate of a region acts as a control, establishing boundaries within which only certain crops can grow. Limiting variables may include temperature, light, and precipitation. In addition, the effect of climate on an organism may be magnified by other environmental stresses, rendering it more susceptible to pests, disease, or damage.

Alberta already exists at the margin of productive agriculture land. In this position, it is increasingly sensitive to climatic variability. Measures can be taken to adapt agricultural practices to a variable climate. Firstly, new strains of crops, such as early maturing wheat or drought resistant forage, are being developed. Secondly, the climate can be modified; irrigation schemes, greenhouses, and windbreaks are attempts to ameliorate climate.

A number of agricultural regions around Alberta have been discussed in the literature. Bailey (1981) discussed the agricultural climate of the Peace River region. He pointed out that although the air temperature and thermal regime were important, the seasonality of precipitation was crucial to crop production. Year-to-year precipitation during the growing season can be highly variable. In this region, high precipitation during the harvest period is particularly hazardous.

The agricultural climate of the Lethbridge region was discussed by Hobbs (1977). Using historical records dating back to 1902, he summarized the basic climate parameters of temperature, precipitation, sunshine, winds, evaporation, relative humidity, and soil temperatures.

Considerable research has been undertaken on frost-free periods in the province. Most cereal crops require a 90-day frost-free period. However, Longley (1967) cautioned that data on frost-free periods should only be used as a guide when making agricultural decisions. Davies (1972) discussed the frost-free period in the Lesser Slave Lake area. For hazardous areas around the lake, he recommended mixed farming to reduce the risk and impact of frost occurrences.

High wind speeds and soil erosion are a serious problem in the agricultural areas of the province. Toogood (1978) stated the need for more data on wind speeds and direction. Geitz (1983) examined the erosive potential of wind. He pointed out that the rate of wind erosion is strongly affected by agricultural practices such as summer fallowing. The erosive potential of wind varies spatially and temporally. Information on the direction of erosive winds is used in determining the optimum placement of shelterbelts, and the orientation of strip cropping, soil ridging, and cultivation.

In Alberta, the variability of the climate is a major hazard to the agriculture industry. Bumper crop yields may be followed by crop failures because of climate vagaries. Findlay (1981) stated that drought is not simply the result of insufficient rainfall. Land use practices, pests, disease, fire, and recent changes in technology may all contribute to bringing on drought.

In order to assess the impact of drought, Findlay recommended that close attention be given to its regional timing and geographic extent. Climatologists must work with economists to document the effects of drought on hydroelectric power, water supplies, crops and livestock, and the development of social policy. Modelling future drought scenarios based on possible climatological conditions will lead to better strategies to cope with the inevitable droughts of the future.

Grace (1986) discussed the interactions of climatically related variables and their effects on agriculture. For example, in both 1984 and 1985, severe grasshopper outbreaks were recorded for June through August. The climatic conditions that resulted in drought and crop losses were responsible for the invasion of these pests. Direct losses due to grasshopper populations were estimated to exceed $100 million in Alberta and Saskatchewan. This illustrates a secondary effect of climatic variability on the Prairies.

### 4.1.2 Forestry

Forestry in Alberta generates millions of dollars of revenue and employs hundreds of people; it is one of the mainstays of our economy. Understanding climate principles is fundamental to successful forest management. Forests in Alberta are subject to widely contrasting temperature and precipitation regimes. Their spatial and temporal origins, growth rates, species, longevities, and total accumulated biomass reflect past and present climate conditions.

The most important, dependent variable in forestry is biomass accumulation. The object of a study by Peterson et al. (1983) was to review all factors that cause changes in biomass accumulation and to assess which factors were determined by climate variables. A sample of temperature factors contributing to an increase in biomass accumulation include:

1. Increased mean summer temperature; and
2. Increased degree days over 10°C for June and July.

Three temperature factors leading to a decrease in biomass accumulation include:

1. Increased temperature in the prior August;
2. Increased winter-early spring temperature; and
3. Increased plant stress due to warm temperatures while the soil is still frozen.

Biomass accumulation can also be affected by insolation, precipitation, air mass, and wind factors.

Forest fires can quickly destroy acres of forest. The potential occurrence of forest fires and their rate of spread are direct functions of climate. Janz (1982) stated that "forest fire incidence in Alberta can be considered a rough indicator of climate variability." He refers to the forest fires of 1980 and 1981 as examples of what extreme climatic variability can do to Alberta forests. The major fires of 1980 were caused by man, while the fires of 1981 were lightning-induced.

Researchers at the Northern Forest Research Centre have studied the effect of clearcutting on the microclimate of forests (Singh 1986). Microclimatic changes can affect the early growth and survival of planted seedlings in the cut blocks. Small increases in mean ground and soil temperatures were noted during July and August. These changes must be considered in conjunction with rainfall patterns to determine their combined effect on the growth and survival of seedlings planted in the clear-cut areas. The increase in mean temperatures could be beneficial under adequate moisture supply; the reverse could be true under drought conditions.

### 4.1.3 Hydrology

The study of climate and hydrology is of paramount importance in Alberta. Snow is present in the Rocky Mountains year-round and impacts the hydrologic cycle of the prairies. All components of the hydrologic cycle including evaporation, transpiration, precipitation, and runoff are climatically controlled. Hydrologists must be cognizant of the climate characteristics of the region of interest and of climate processes.

The climatology of severe rainstorms has been discussed extensively by Verschuren and Wojtiw (1980) and Wojtiw and Verschuren (1981). The first publication dealt with estimating maximum probable precipitation for Alberta river basins, while the latter study examined severe rainstorms. The four major areas of severe rainfall in Alberta are: (1) south of Calgary; (2) from Edson to Edmonton; (3) from Lesser Slave Lake to Fort McMurray; and (4) the Fort Chipewyan region. The greatest frequency of severe rainfall events is in June for southern Alberta and in July for central Alberta. The concept of maximum probable precipitation has ramifications for water supply management strategies. The authors concluded that at least 85% of the severe storms in Alberta result from cold, low pressure systems. Their techniques can be used in flood forecasting and river basin management. Wojtiw and Verschuren (1981) found that flooding episodes in Alberta, which occur predominantly in the south, are usually due to extreme rainfall preceded by below normal temperatures. Nemanishen (1977) found that flood forecasting could be improved by incorporating river basin physiographic and climatological factors.

Flood forecasting and the analysis of severe precipitation events has been aided by new weather radar technology. These data not only augment the precipitation data from traditional precipitation networks, but can also determine rainfall rates and amounts between network stations. A number of publications explore the usage of radar data and its applications to water management (Barge and Humphries 1977; Humphries 1983; Wojtiw 1986a).

A number of researchers have studied snow and its management (Barnaby 1980, 1982; Golding 1977, 1978; Louie 1977; Nkemdirim and Benoit 1975; Storr 1973, 1974). Snow is a unique component of the hydrologic cycle as it has the ability to store precipitation and release it to the system at a later date. Snow management is, therefore, of great importance to runoff, flood and irrigation, and energy-balance studies. Storr (1973) looked for the best design of artificial clearings to optimize the use of snow water. Golding (1978) was interested in how chinooks related to snowmelt and the effect on watershed management. He concluded that during chinooks there was a significant snow moisture loss due to evaporation.

These hydrologic studies show the variety of ways that climatology can be applied to other sciences. Flood and drought forecasting, and irrigation management all benefit from joint applications of hydrology and climatology.

## 4.2 AREAS OF MINIMAL RESEARCH

Research in several economic sectors of importance to Alberta is almost non-existent. Four such sectors are highlighted.

### 4.2.1 Tourism and Recreation

Tourism is a multi-million dollar industry in Alberta and has been identified as an area of potential economic growth. Recreational activities attract people to the province and enrich the lives of those who live here.

A benchmark study of the tourism and outdoor recreation climate of the prairie provinces was completed in 1975 (Masterton et al. 1975). For various recreational activities, such as landscape touring or skiing, the concept of an activity day was developed. For each activity, specific climate conditions must be met for its designation as a suitable day. For example, a suitable day for skiing must have a temperature warmer than -14°C, visibility greater than 0.8 km, windspeeds less than 7 m/s, and more than 2.5 cm of snow cover. Using this information, the number of suitable days for each activity was mapped for the prairie provinces. This report is repeatedly referred to by other authors as a classic study in recreation (Charlton 1976; Cote 1984; Klivokiotis and Thomson 1987; Olson 1985).

Climate information can be incorporated into park planning in several ways. These are:

1. To provide the data necessary for effective management of park resources;
2. To ensure good facility location and design;
3. To ensure visitor safety;
4. To determine characteristics of park seasonality and to try to spread activities to shoulder periods; and
5. To complement education/interpretive programs.

Janz and Storr (1977) in The Climate of the Contiguous Mountain Parks gave a checklist of climatic parameters for recreational site selection including: altitude, precipitation, temperature extremes, wind, and lightning. Ideally, climate data would be integrated into the planning process before decisions leading to on-ground facilities are finalized (Alberta Climatological Association 1980).

### 4.2.2 Building Design, Transportation, Construction

Research on the impact of climate on building design, transportation, or construction is limited and difficult to find in Alberta. We welcome suggestions or information from members of the transportation or construction associations, architects, and others participating in the Symposium.

## 4.3 SUMMARY AND RESEARCH DIRECTIONS

Climate research activities have focussed on a wide variety of topics. Over one-quarter of the references dealt with hydrology and resource industries such as agriculture and forestry. These sectors are particularly sensitive to climatic variability.

Little research has been published dealing with topics such as recreation and tourism, building design, construction, or transportation.

Indeed, these subjects accounted for only 3% of the total references. These industries are impacted by climatic conditions and could benefit from including climate in their planning processes.

Climate research in the recent past was concerned largely with weather modifications, the hail and snow studies of the Alberta Research Council, lightning and forest fire climatologies, and water management studies. Drought was a major concern as reflected by the related research into soil erosion, severe grasshopper outbreaks, forest fires, precipitation climatologies, and snow management.

The next step for applied climate research is to quantify the direct and indirect relationships between climate and the resource sectors. More work is required on the constraints and incentives that influence how society responds to climatic variability. What characteristics of society make it resilient to climatic variability and change? Furthermore, how can society take advantage of and benefit from climatic variability and change? These questions will guide research activities in the coming years.

In conclusion, the main priority areas which require research attention are:

1. Improved long-range forecasts geared to the resource industries;
2. Additional and improved data bases, not only of climate data per se, but on the costs incurred in sectors such as tourism, architecture, and agriculture due to the climate;
3. Technological developments; and
4. Regional-based modelling studies on the impact of climatic variability and change on the environment and its resources.

Some of these research areas were also identified by Leggat et al. (1981). Particular attention to these issues will help our society adapt more easily to inevitable climatic variability and change.

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# THE LINK BETWEEN CLIMATE AND AGRICULTURE: CAN WE DEAL SIMPLY WITH A COMPLEX SITUATION

by

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## ABSTRACT

Weather conditions are primarily responsible for the difference between a great crop year and a poor crop year. Climate information, however, assembles daily weather data in years (e.g., monthly total precipitation). However, crops respond to the unique combinations of daily weather events, which are only poorly represented by climate statistics.

The use of methods, which were once appropriate for understanding climate differences and crop potentials on a global or continental scale, is not appropriate for depicting the link between climate and agriculture on a provincial scale.

Estimates of average crop prospects are not sufficient for planning purposes in a time when sophisticated economic analysis and decision making methods require detailed information on risk versus reward. In agriculture, a major risk is weather. How we handle climate data must recognize this and provide the risk information needed. The wider use of daily weather data in soil water models, coupled with crop growth models, should provide the type of information which better describes the link between climate and agriculture.

## 1. INTRODUCTION

The possibility of climatic change and the associated potential impacts have been the subject of much discussion over the past few years. If the impact of climatic change on agriculture is to be assessed, the response of agricultural production to climatic variability in the past must first be understood and quantified. This paper discusses the link between agriculture and climate.

## 2. LINK BETWEEN AGRICULTURE AND CLIMATE

Climatic information is needed for planning purposes. Societies, acting through governments, use a planning process to minimize climatic risk to life and property, and to optimize the use of available resources. In agriculture, minimizing risk is an important element in planning crop production and harvesting operations. Available climatic data are used to estimate agricultural potential for small-scale planning. The challenge is to also make it useful for large-scale or farm-level planning.

Climate and its weather components pose one of the major risks to agriculture in Alberta. The value and usefulness of climatic information are determined by the extent to which it aids or improves the planning process. What is the climatic risk to agriculture? How do we obtain information from climatic data on the risk to agricultural production?

Available climatic information is presented as a variety of statistics for a defined normal period. Climatic normals facilitate comparison of climates for different locations. The information is summarized and presented in a format intended to serve a broad range of users and applications. It is left to the user's skill and judgement to interpret the climatic information for their own application. These means and standard deviations provide indirect information on climatic risk to agricultural production.

Crop production integrates the daily weather. Mean climate does not correlate to mean crop response. For example, the timing of precipitation is a crucial factor governing the success of dryland agricultural production in Alberta. During the 1987 growing season, there was significant moisture stress in late June through July, followed, in August, by flooding in some areas. The combination of a prolonged dry period followed by a very wet interval produced a growing season precipitation value that was near "normal". But (in many areas) the actual timing of growing season precipitation was detrimental to crops. Widely varied weather sequences can produce similar growing season or annual means of climatic parameters; yet crop response can vary widely for similar, long-period climatic values.

What is required from climatic data is information on the climatic risk for specific agricultural enterprises. It must be recognized that the agricultural industry is diverse. In Alberta, the range of agricultural enterprises includes the production of major cereal grains, oilseeds, forages, horticultural crops, specialty crops, and apiculture. It has a variety of livestock operations, primarily beef cattle, but also including dairy, sheep, and poultry. Climatic hazards, such as water supply shortages and cold temperatures, pose a threat to livestock operations and need to be considered in enterprise planning. It is crop production where climate generally accounts for the greatest degree of risk.

An excellent demonstration of interpreting climatic data to present information on risk is found in the workday probabilities (e.g., Rutledge and McHardy 1968; Selirio and Brown 1972) and technical bulletins on "Risk Analysis of Weekly Climatic Data for Agricultural and Irrigation Planning" (Coligado et al. 1968). The former papers deal with a specific agricultural concern (field trafficability); the latter provides a variety of selected basic and derived climatic parameters relevant to agriculture. In both instances, considerable user skill and judgement are required to interpret the information's applicability to an agricultural enterprise. These examples demonstrate one approach, but their products do not provide good information on either the risks or potential of crop production.

The paper by Dr. Shaykewich (Shaykewich and Dunlop 1988), presented earlier in this Workshop, demonstrated some of the problems and inadequacies of using climate normals. Normals provide a way of quickly comparing the climatic statistics of different locations. Normals have been used at a small scale to estimate crop production potential and the impact of climatic change on agriculture (Dumanski and Stewart 1981; Williams et al. 1986). But they do not do a good job of helping to plan activities on the farm.

The paper given by Dr. Parry (Parry 1988), at this Workshop, has touched on the importance of considering scale, both in space and time, when determining requirements and evaluating methods of satisfying them. There is a mismatch of temporal scale between the requirements of agricultural producers and the available climatic information. The information does not provide sufficient detail, in a meaningful or useful form, on expected climatic variabilities. Parry (1986) states "One way of evaluating climatic change in human terms is therefore to consider it as a *change in level of risk*, that is, in the probability of an adverse or beneficial event, such as a shortfall from some critical level of output or excess above expected yield." The climatic risk to crop production has not yet been determined in terms suitable for use in farm planning.

The effect of climatic variability must be presented in a meaningful and useful way. It is difficult to convince people of the possibility of climatic change when, for many years, they have been provided with information which has portrayed climate as static. There is a need to present information on the effect of climatic variability on agricultural production.

Frost data are good examples of climatic information presented as probabilities. Combining frost data with heat units and precipitation, as conditional probabilities, is an available option. The problem is the form of presentation. The accompanying explanations can be imposing and complicated, and the information is not easily understood; consequently, it is often not used.

A person planning an agricultural enterprise is not so much concerned about climate, but as to how it translates to the risk of growing a crop. Climatic information is most often presented as means, when what is needed is information on the probability distribution of crop yields. The paper presented by Dr. Stewart (Stewart et al. 1988), at this Workshop, is an example of the type of information required. Their model's strength is that it provides information on the climatic risk to crop production. The problem with the model is that it is still at the development stage and is not readily transferable into widespread use.

Crop models are a way to link knowledge about crop requirements with the data available on climate and soil resources. The use of mathematical models to interpret climatic data for specific applications is widely accepted and there is a large body of literature on crop models. However, a major obstacle to their wider use is the absence of detailed information on their required inputs. Crop models that use long-term, normal climatic data as inputs may suit impact assessment needs, but they do not provide useful farm planning information. There is a need to use crop growth and development models to interpret climatic data for annual agricultural applications. Further, these models must be able to incorporate available soil information to make them meaningful, rather than demonstrative. The abundant climatic data available must be applied to farm level planning if it is to be viewed as valuable for agricultural producers.

The biological processes operating during the growth of a crop are complex. Crop growth models using actual daily climatic data do not solve the problem of how to adequately handle these complex, crudely parameterized processes. However, the benefit of using daily data is that it provides the best information on the effect of precipitation amounts and timing on crop growth. The output of crop models can be useful to crop producers if it presents relevant information on the probability distribution of yield for a given crop type, in a given location, for a particular soil type.

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# A PROPOSED GOVERNMENT RESPONSE TO DROUGHT

by

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## ABSTRACT

A cooperative approach to drought mitigation is proposed. The objectives of the program are to maximize our reliance on long-term, "on-going" programs and to improve our drought monitoring, analysis, communications, and response procedures. This will provide a more effective and efficient drought mitigation program.

Components of a new government response strategy would include an automated western drought monitoring network, a drought monitoring and analytical service, and a preplanned communications strategy. A provincial technical drought monitoring and evaluation committee is recommended in addition to a senior federal-provincial drought response committee.

## 1. INTRODUCTION

Here in Western Canada, we experience large scale fluctuations in temperatures and wet and dry cycles. The recurrence of widespread dry periods in recent years (e.g., 1977, 1980, 1984, and 1985) underscores the influence that drought has on our lives. A 1983 study by C.D.V. Williams (Williams 1986) determined, that from 1929 to 1980, wheat or cereal droughts affected part of the prairie provinces in 26 years and some part of the Palliser Triangle in most years. Drought studies carried out by Prairie Farm Rehabilitation Administration (PFRA) and the Saskatchewan government evaluated the yield of four major crops during the 1930 to 1979 period. It was determined that in Saskatchewan the Palliser Region incurred 50 percent of the total provincial loss in crop production due to drought.

No area in the prairie provinces is free from the occurrence of drought. For example, in 1986 and 1987 the Tisdale area of northeast Saskatchewan experienced low soil moisture, low runoff, increased demand for dugout pumping services, and decreased pumping rates in some shallow wells. Further, Saskatchewan Crop Insurance records show that drought related indemnities were paid in almost all of their 23 crop risk areas in every year during 1972 to 1980.

A review of the 1980s would identify no year (whether it may have been described as an average year, drought year, or record crop production year) when drought stress was not a factor of concern, or water was not in short supply, somewhere in western Canada.

Virtually every aspect of community activity has been influenced by droughts: population, personal income, and every sector of the economy. Our perception of drought is commonly that of short crops burning in the field, dry pastures and empty sloughs, dust and drifting soil. However, some of the most significant financial and social impacts are felt well beyond the farm gate.

## 2. DROUGHT MITIGATION

Because of the recurrence of drought and its far reaching impact, governments have taken on the task of drought mitigation. Traditionally, drought assistance has taken the form of long-term, on-going programs, and short-term initiatives. The long-term programs are designed to develop land and water resources and to provide a safeguard against the normal vagaries of weather and climate. Long-term drought assistance has primarily been available through:

1. Federal/provincial crop insurance programs;
2. Technical and financial support for the development of secure water supplies;
3. Research and development of drought tolerant crop varieties; and
4. Research and development of soil and water conservation practices such as shelterbelts, community pastures for the management of marginal lands, erosion control, and dryland salinity investigations.

There are numerous agencies involved in the operation and delivery of agricultural and community, or urban, drought related programs in the prairie provinces. The Prairie Farm Rehabilitation Act provides for the rehabilitation of drought and soil drifting areas in the Provinces of Manitoba, Saskatchewan, and Alberta. Within these areas it develops and promotes systems of farm practice, tree culture, water supply, land utilization, and land settlement that will afford greater economic security. This systematic federal participation in responding to drought originated during the drought era of the 1930s. Today, the technical and financial assistance which is provided for the development of secure water supplies and conservation of fragile lands is carried out jointly with, or complements, provincial programs.

To further reduce the need for ad hoc financial assistance programs, a form of income stabilization was introduced in 1939 through the Prairie Farm Assistance Act (PFAA). This program's intent was to respond to declines both in price and regional production. Farmers were levied 1% of their grain sales during "normal" times. In the event of price declines, or regional crop losses due to events such as drought, they were eligible for specified payouts. The program was not actuarially sound. By 1962, it had incurred a deficit of almost $200 million. In addition, extremely poor weather conditions between 1959 and 1961 led to further federal disaster assistance, in the form of acreage payments, of about $125 million to western producers.

The deficiencies of the PFAA program lead the federal and provincial governments to instigate actuarially sound crop insurance programs. In 1959, federal legislation was enacted under which individual federal/provincial crop insurance agreements could be entered into. At present, all 10 provinces have crop insurance programs. In the prairie provinces, the cost sharing formula calls for the provinces to pay all administrative costs and the federal government and producers to equally share the cost of insurance premiums. The object of these programs is to guarantee producers sufficient return per acre to cover out-of-pocket expenditures incurred in attempting to grow their crop.

Short-term programs are another form of drought assistance. The short-term programs tend to be of an ad hoc emergency nature. These are government responses to the pressures brought on by our knowledge of the potential for undue hardships caused by drought. These programs have included:

1. Fodder transportation assistance;
2. Livestock transportation assistance;
3. Livestock financial assistance;
4. Temporary drought emergency water supply;
5. Crop drought financial assistance;
6. Emergency dugout pumping;
7. Debt adjustment; and
8. Beekeepers assistance.

Governments were called upon to provide these additional forms of assistance in 1961, 1977, 1980, and again during the 1984 to 1985 droughts.

Generally, experience shows that short-term, ad hoc, responses to drought lead to less effective, less coordinated, and untimely programs.

The perception of drought conditions during these times of panic vary considerably. In fact, drought is an ever changing phenomenon. A review of press coverage prepared by Environment Canada during the 1980 drought on the Prairies gives the impression that "newspapers were negative on government mitigation efforts, implying bureaucratic delay and government indecision with respect to drought aid". According to the report, "newspapers reporting on the 1980 drought and its effects determined to a considerable extent how people perceived the drought conditions". These kinds of experiences demonstrated the need to better understand drought, and to further develop drought mitigative measures that would be included in a government response strategy. Therefore, the Governments of Canada, Saskatchewan, and Manitoba engaged in detailed studies of the physical and economic impacts of drought and potential mitigative measures. The 1984 to 1985 prairie drought provided further insight, and strengthened the conclusions, on tackling back-to-back droughts.

The Government of Alberta formed a provincial "Drought Monitoring Committee" composed of representatives of various departments and agencies, including federal representation from PFRA. The committee convenes early each year to review conditions as reported by various committee members. This committee then recommends appropriate drought responses to the Agriculture and Environment Ministers.

## 3. OBJECTIVES OF A GOVERNMENT RESPONSE SYSTEM

The purpose of this paper is to propose a cooperative government response system for Western Canada that will address existing needs. This proposal is being taken to the provinces to stimulate discussion and to work toward common understanding and agreements on a drought response process. The objectives of this proposed drought response system are to:

1. **Improve information and communication.** It is necessary to evaluate the information needs of both the public and the program implementors to ensure that all required information is available. The system should provide reliable information for the public, media, and decision makers. Communication of this information is the key to providing an effective drought response. Information dissemination plans are defined by the drought response system.
2. **Standardize the drought designation procedures.** A methodology for defining drought and identifying actuation levels based on its location, intensity, and duration will provide clear signals to induce government action.

3. **Improve drought impact analysis** to enable the physical, social, and economic consequences of drought to be readily evaluated. Mitigative measures can be tested in advance to determine the most effective strategies.
4. **Improve mitigative action** with pre-planned programs. Clearly defined and well publicized long-term, "on-going" programs are a major part of an effective drought response. Short-term, "on-shelf" programs, with pre-planned actuation levels and administration, may be a necessary response to prolonged back-to-back droughts. The pre-planned response becomes systematic, coordinated, and more efficient in reaching policy objectives.
5. **Establish federal and provincial cooperation** in monitoring and analyses, and the delivery of the most effective programs.

## 4. ASSUMPTIONS

The proposed government response strategy is based on the following assumptions.

1. The response process would cover the agricultural regions of the prairie provinces and would extend into British Columbia.
2. The process could be coordinated by agreements with the three prairie provinces and British Columbia.
3. The expertise required to monitor, assess, and make recommendations on drought response should be available on a continuing basis in a single agency.

## 5. BASIC ELEMENTS OF A GOVERNMENT RESPONSE STRATEGY

A cooperative interagency government response strategy would be composed of the following basic elements:

1. **An automated western drought monitoring network** responsible for the collection of current near-real-time data including weather, streamflows, and reservoir volumes. This could be accomplished by better coordination and enhancement of existing monitoring programs.

2. **A drought monitoring and analytical service** would analyze basic data, develop drought indicators, and prepare and evaluate drought scenarios to establish and pre-plan response options. It would provide social and economic analysis to determine the consequences of current or possible drought conditions. This service would provide the linkage between federal and provincial research and monitoring agencies, and agencies delivering drought assistance programs. The service would also promote cost-efficient drought analysis by ensuring that all contributing agencies have clearly defined and complementary work.
3. **Provincial technical drought monitoring and evaluation committees** would be an integral component of the analytical activity. This would ensure provincial input and provide a provincial technical review of the analytical results. These provincial committees would also initiate required activities within their jurisdictions.
4. **A cooperative pre-planned communication strategy** would be maintained as part of the drought monitoring function. This would ensure that timely and accurate information is provided to the media and the agricultural industry, and is shared between government agencies. Briefings and recommendations would be continually passed on to decision makers. These recommendations would be based on the drought assessment, existing long-term, "on-going" programs, and pre-planned, short-term program options necessary under extenuating circumstances.
5. **In each of the provinces, a senior "Federal-Provincial Drought Response Committee" may be established.** These senior committees would meet in response to recommendations made by the drought monitoring and analytical service, and the technical committees, based on a planned alert procedure. The senior committee would be responsible for reviewing the information and recommendations from the drought monitoring and analytical service, and the technical committees. It would evaluate the droughts' significance on a

provincial basis. Development and maintenance of provincial drought response plans and the responsibility for advising the heads of represented agencies would lie with the Senior Drought Response Committee. A federal/provincial communications plan would be developed and implemented by each provincial committee to ensure that information on drought is quickly and efficiently made public.

6. **In response to a prairie-wide drought, a meeting of Deputy Ministers of Federal and Provincial Departments of Agriculture would be called when established trigger mechanisms warrant the consideration of emergency actions beyond the "on-going" drought mitigating programs.** Federal-provincial drought response options and recommendations would be reviewed. Having direct access to political decision makers, provincially and federally, the Deputy Ministers would recommend necessary emergency actions to the Ministers.
7. **The decision to implement a particular federal/provincial drought response program would be made by the appropriate Ministers.** Having been pre-planned, the program delivery would depend on the resources identified by the planning process.

The cooperative process outlined in elements 5, 6, and 7 are a suggested framework for inter-agency information exchange. This process would allow the exchange of technical drought information, ongoing programs, and previous drought assistance programs; and the recognition of existing decision making processes within federal and provincial governments. This process is based on the general information exchange and decision making procedures that have been used to address drought in the past.

## 6. MONITORING AND DROUGHT INDICATORS

An important link in the drought response system is the acquisition of near-real-time data and information on the availability of water supplies. The Prairie drought monitoring network should be more automated in terms of on-line data transmission. Systematic evaluation of current physical, meteorological, and hydrological criteria, in relation to potential productivity, would provide more timely and objective information on the potential for drought impacts.

Because drought is an ever changing phenomenon, dependent on many variables, a number of indicators are used to evaluate the potential for reduced yields in agriculture and for water shortages in other economic sectors. These indicators should be used to trigger such responses as:

1. Information dissemination;
2. Planning and enhancing long-term programs such as dugout pumping and deep-well assistance;
3. Evaluating the socio-economic need for short-term programs; and
4. Local drought mitigative action to control the demand for water and its use.

Different regions of the prairie provinces are affected by drought to varying degrees depending on soil type, crop varieties, water storage capabilities, supply and demand, and losses due to evaporation and waste. Mismanagement can exacerbate or create a drought situation; efficient land and water management can reduce the effects of drought.

Because a lack of precipitation is the first signal of an impending water shortage, it is the best drought indicator. A return of average rainfall conditions is a signal that the drought may end. However, to be more specific about the severity and impact of drought, data are needed on current and normal conditions of soil moisture, snow pack accumulation, temperature, wind, evaporation and evapotranspiration, crop yield estimates, and reservoir, dugout, and groundwater storage levels.

There is a considerable amount of data available including:

1. Weather and climate data from the Atmospheric Environment Service and non-standard data;
2. Hydrometric data;
3. Snowpack data;
4. Quantitative and qualitative information on soil moisture;
5. Groundwater observation well networks;
6. Reservoir level recording;

7. Farm, community, and urban water supply reports; and
8. Pasture, forage, and crop condition reports.

In support of data requirements, new technology and evaluation techniques are being developed and applied to drought assessment. Some of these developments include:

1. Electronic data transmission;
2. Assessment of wind erosion potential;
3. Remote sensing, such as weather radar and satellite imagery, for applications such as a crop monitoring system;
4. Long-range weather and climate forecasting;
5. Groundwater level trend forecasting;
6. Geographical information systems for the storage, manipulation, evaluation, and presentation of data; and
7. Socio-economic models to evaluate the consequences of drought.

In order to become more efficient and effective in the application of this information, standard drought determination procedures and methodologies are required. For example, this paper will briefly describe the case of agricultural drought. Data on land characteristics, land use, and climatic normals should be collected and archived on an on-line system. Current weather information should be transmitted through an automated Prairie Drought Monitoring and Analysis Network.

Data should be stored on-line and linked to a Geographical Information System (GIS). Uniform Productivity Areas (U.P.A.) for the prairie provinces have been developed through a joint effort by the Canada Centre for Remote Sensing, the University of Waterloo, and Agriculture Canada. An U.P.A. (similar in concept to Crop Insurance Risk Areas) is defined by soil landscape boundaries. It has a uniformity of agricultural productivity and satellite spectral response due to its homogeneous soil-climatic regions and soil texture.

A verification process is required to establish the effectiveness of the U.P.A., or any similarly soil-climate-land use unit, in representing an area of uniform production capability for grains, forage, and other agricultural products.

Once these uniform units have been refined and verified, they should provide an area appropriate for the evaluation of drought conditions. Relevant data may then be compiled for each area unit. This would include climatic normals, average long-term crop yields, median annual unit runoff, information on water storages, water demands, and livestock production, and current conditions.

Using the U.P.A.s as a base for defining drought areas, a set of alert mechanisms would be defined for the agricultural drought. Each U.P.A would be evaluated on an ongoing basis using agreed indicators to define the level of drought alert. Under normal circumstances, regular programming activities would be carried out in an effort to provide long-term drought mitigation. When a particular indicator reached a predefined level, a "yellow alert", information would be passed on to various levels in the drought response system and senior government officials would be informed. Communication with the media would be carried out to inform the public on drought conditions and relevant government activity.

Economic and socio-economic models, developed in Manitoba and Saskatchewan during the Drought Studies, would be maintained and updated as required. Similar models should be developed for Alberta. This would facilitate an evaluation of program options for pre-planning, drought impact analysis, evaluating the effectiveness of current mitigative programs, and other farm level drought measures.

## 7. PROGRAM OPTIONS

Briefly, what are the program options? The long-term, "on-going" programs are considered to be the primary source of drought mitigation. These programs are designed to develop and conserve our land and water resources and to provide a safeguard against the normal vagaries of weather and climate.

For agriculture, crop insurance is considered the best tripartite solution to smooth out the known variations in yield. It is apparent from the 1984 to 1985 drought that crop insurance requires some adjustment to provide a higher level of assistance and to ensure that claimants are not penalized when payments are made during a severe drought period. This would provide an extended safe guard for locations that experience consecutive years of drought. Crop insurance organizations are reviewing their programs and addressing short-comings. The report of the Alberta Review Panel Canada-Alberta Crop Insurance, published in December 1986, makes a number of recommendations toward improving insurance coverage. Livestock feed security programs have been introduced in the prairie provinces to provide an on-going protection for the livestock industry.

Among the measures that will most likely continue to be important policy instruments in a long-term drought-proofing strategy are: deep-well assistance, dugout assistance, dugout rehabilitation, the development of permanent water transmission systems, farm irrigation assistance, rural community and urban water infrastructure assistance, assistance for the improved management of marginal lands, shelterbelts, the rehabilitation of eroded or saline lands, agricultural research, and other soil and water conservation and development initiatives.

Short-term programs should be designed to react to the less frequent, more intense and prolonged drought periods. We have learned through the Saskatchewan Drought Studies, and the 1984 to 1985 drought experience, that consecutive years of drought pressure the agriculture water supplies, which in turn ripples through the local, regional, provincial, and national economies. Existing programs are often not capable of providing an acceptable drought buffer; additional assistance is required in view of these unforeseeable circumstances.

An attempt must be made, therefore, to pre-plan short-term assistance based on past experiences and successful programs. Short-term programs, however, must also be flexible. Each drought will be spatially, temporally, intensively, and durationally unique. Every drought will occur under a different set of social, economic, and political conditions.

Finally, there is the issue of lasting climatic change. Are the programs of today capable of providing a sufficient drought buffer under future climatic conditions? What changes will be required to ensure a desirable level of drought mitigation? These are questions that agencies such as PFRA are beginning to ask in view of the potential for drier agricultural conditions. At present, the level of understanding about future ramifications of the Greenhouse Effect does not provide sufficient regional acuity to begin to answer these questions. However, when climatologists are able to provide more reliable predictions, and as the climate begins to noticeably change, agricultural policies and long range plans will begin to take these factors into account.

## 8. CONCLUSION

This paper attempts to briefly describe the essential parts of a cooperative government response system. The objectives are to maximize our reliance on long-term, "on-going" programs and to improve our drought monitoring, analysis, communications, and response procedures. The purposes are to provide more effective and efficient drought mitigations programming and to eliminate the ad hoc approach to emergency management.

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# AN OVERVIEW OF THE EFFECTS OF CLIMATIC CHANGE AND CLIMATIC VARIABILITY ON FOREST VEGETATION IN WESTERN CANADA

by

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## ABSTRACT

Climate warming in the post-glacial periods is known to have produced shifts in the existing boundaries of forest vegetation. This is likely to occur through the doubling of atmospheric $CO_2$ and the attendant warming trend which is being predicted with increased certainty. The forestry sector, a major component of Canada's economy, would be affected in many ways. Climatic change will impact on forest productivity, wood quality, forest soils, forest insects and diseases, forest logging, natural regeneration, forest hydrology, and forest fires. The frequency and intensity of droughts in a warmer climate need to be explored as these affect the survival and growth of seedlings to replace the areas cut or burned. Research must be undertaken to identify and study all impacts, as these have tremendous implications for the prairie provinces due to significant shifts in agricultural and forestry zones.

The boreal forest is one of the largest remaining tracts of forest land in northern America. It fulfills many important nonmarket functions in addition to being an important source of timber and fibre. According to some economists, the very existence of the boreal forest and its role in the world ecosystem is of greater significance than even its commercial value. Any change in its market and nonmarket functions would, therefore, need to be investigated and assessed thoroughly.

Global $CO_2$ enrichment will have both direct and indirect effects on plant species of the boreal forest. Enhanced $CO_2$ will increase productivity through direct effects on photosynthesis and water-use efficiency. Global warming resulting from $CO_2$ accumulation will be particularly pronounced at boreal latitudes and may increase forest productivity through acceleration of physiological processes and through lengthening of the growing season. The effects of changing patterns of precipitation are less clear.

Ecosystem functioning will be strongly affected; natural succession, nutrient cycling, browsing and grazing, and competitive interactions will all change. The effects of these changes on forest structure and productivity will depend on the relative response of individual species. Economically important tree species could become more, or less, successful depending on how they react to other species. Boundaries of the boreal forest in the prairie

provinces are likely to be pushed northward by as much as 700 km. Areas currently occupied by boreal forest communities may become occupied by grass or brushland or by temperate forests, depending largely on the amounts of precipitation. Long-term studies of responses of important boreal tree species to enhanced $CO_2$ are needed. Similarly, a modelling effort designed to allow reasonable evaluation of complicated ecosystem functioning is urgently required so that system response to changing climate and atmospheric makeup can be studied.

## 1. INTRODUCTION

Although many factors may be involved in affecting climatic change, accumulation of greenhouse gases, especially carbon dioxide ($CO_2$), has large implications. Atmospheric levels of $CO_2$ have increased from about 283 ppm in 1860 to 340 ppm in 1983 (Gates 1983; Plass 1959); during the past decade, $CO_2$ concentrations increased at an average rate of 1.5 ppm per year. It is expected that the continued use of fossil fuels, and deforestation especially in the tropics, will produce $CO_2$ levels as high as 600 ppm within the next century (Bacastow and Keeling 1973). Hengeveld (1987) predicts levels of 1040 ppm under rapid growth/conventional fuel scenarios, or 700 ppm under energy efficient scenarios, by 2100 AD. Because of the infrared absorption qualities of its molecule, an increase in atmospheric $CO_2$ concentration is predicted to cause global warming, alteration of atmospheric pressure patterns, and changes in precipitation patterns and amounts.

Recent studies indicate that a doubling of $CO_2$ concentration may increase average summer temperatures of the earth by 3.5 to 4.5$^{o}$C (Environment Canada 1986). Such a warming is greater than any climatic change experienced during a relatively short period in the past 10 000 years. These studies also suggest that within the next half century, central Canada could experience a mid-summer warming of as much as 9$^{o}$C with a corresponding 50% reduction in soil moisture. Increased temperatures and aridity will, therefore, affect the growth and quality of forest vegetation in the country.

The temperature effect is expected to be greatest at northern latitudes where long periods of snow cover increase the annual albedo of the land surface (Manabe and Wetherald 1975; Pollard 1985). A large-scale redistribution of global water supplies will be a significant impact of such warming.

Forested areas in western Canada are likely to be affected in several ways. The expected impacts include a direct fertilizer effect of $CO_2$ on plant growth, $CO_2$-induced climatic change on physiological and growth processes of forest species, and changes in the structure and function of western Canadian forest ecosystems.

These impacts are of great importance. In 1984, the value of domestic exports of forest products from the prairie provinces was estimated at $708 million (Canadian Forestry Service 1986). Other forest land uses such as hunting, fishing, camping, and picnicing greatly add to the forests' value. The forests are of great importance as sources of municipal and other water supplies. An understanding of the effects of $CO_2$ enrichment on forest ecosystems is important, therefore, from both a scientific and a practical point of view.

## 2. DIRECT EFFECTS OF $CO_2$ ON TREE SPECIES

The direct effects of enriched $CO_2$ on plants are largely a result of the effects on photosynthesis and water use efficiency (Kramer 1981; Morison 1985). Carbon dioxide is a substrate for photosynthesis; for northern forest species it may limit photosynthetic production even if other necessary factors (e.g., water, nutrients, and light) are not limiting. As a result, most plant species experience a "fertilizer" effect when placed in chronically high levels of $CO_2$. For most species, high levels of $CO_2$ also tend to cause partial stomatal closure. This reduces water loss more than it affects photosynthesis. As a result, water use efficiency (photosynthesis/transpiration) is improved.

Direct effects of $CO_2$ enrichment on boreal forest tree species of the Canadian prairies have not been studied in great detail. Higginbotham et al. (1985) studied growth and photosynthesis of lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) seedlings grown at 330, 1000, and 2000 ppm $CO_2$. Maximum net photosynthetic rates at the three levels were 4.5, 7.2, and 6.5 $mg.dm^{-2}.h^{-1}$. Some fertilization of the photosynthetic process is apparent, even though the highest rates have been observed under normal $CO_2$ levels in other studies (Dykstra 1974). Kramer (1981) points out that maximum stimulation of photosynthesis occurs shortly after a plant's introduction to a high $CO_2$ environment. Over long periods, photosynthetic rates tend to drop towards those exhibited at normal levels of $CO_2$. The plants measured by Higginbotham et al. had been grown under the three $CO_2$ levels for five months when photosynthesis was measured. Photosynthetic data for other boreal forest tree species are not available.

Impacts of high $CO_2$ on water use efficiency of northern tree species appear to be quite variable. Brown[1] found that stomatal resistance of trembling aspen (Populus tremuloides Michx.) increased about three times when plants were grown at approximately 750 ppm compared to those grown at 340 ppm. Higginbotham et al. (1985) found no difference in stomatal resistance of lodgepole pine grown at 330, 1000, or 2000 ppm $CO_2$. In both cases, it is likely that water use efficiency is increased because of photosynthetic increases; transpiration will increase only if the relative humidity decreases and/or temperature increases.

Generally, the growth of tree seedlings is positively correlated with exposure to enhanced $CO_2$ as long as other environmental factors are not growth-limiting. Early increases in photosynthesis are likely channelled into increased leaf production. Although, over time, photosynthetic rates may return to levels similar to those found under ambient levels of $CO_2$, the increased leaf surface area implies long-term growth enhancement. Figures 1 and 2 show lodgepole pine and white spruce [Picea glauca (Moench) Voss] seedling growth response to enriched $CO_2$ (Higginbotham et al. 1985; Higginbotham 1983).

Yeatman (1970) found increases of 61% and 40% in shoot dry weight of three-week old seedlings of white spruce and jack pine (Pinus banksiana Lamb.) grown at 900 ppm $CO_2$ and at ambient conditions respectively.

All studies performed to date on the effects of $CO_2$ enrichment on growth are relatively short-term; no information is available to indicate the long-term effects. In theory, increased growth rates of young plants should be compounded over time, producing mature trees in shorter times than at present. However, early crown closure may create early intra-specific competition, reducing the effect. Other species may respond more readily than trees, causing competitive problems for young trees. While not presently available, such long-term information is clearly needed.

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[1] Brown, K. 1987. Ph.D. student, Dept. Forest Science, University of Alberta, Edmonton. (Unpublished data)

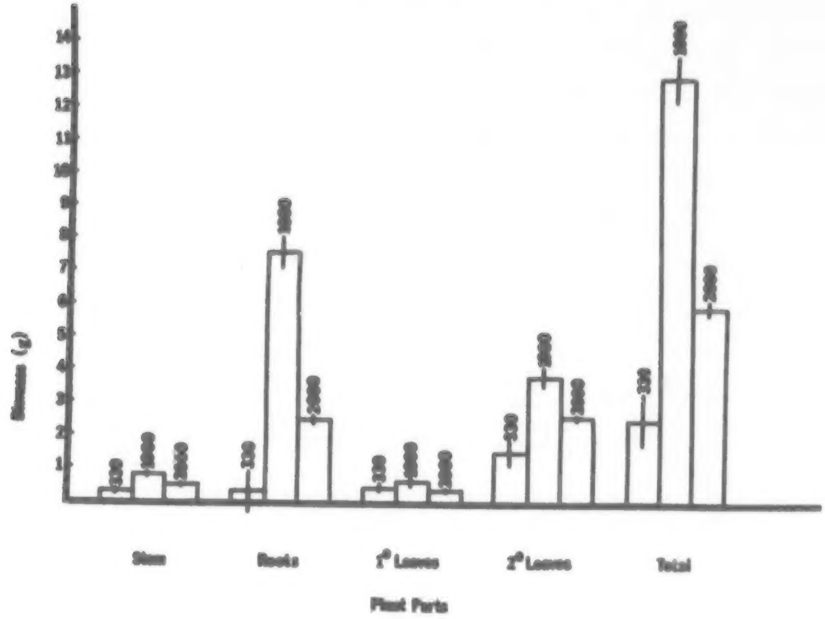

Figure 1. Biomass components of lodgepole pine seedlings grown at 330, 1000, or 2000 ppm $CO_2$. Lines on bars show ± 1 standard error of the mean. (Higginbotham et al. 1985).

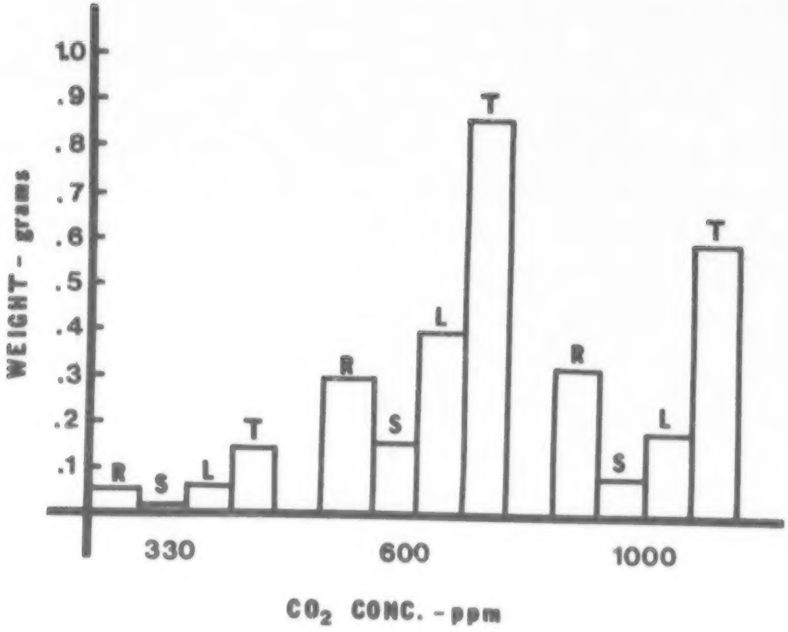

Figure 2. Biomass of roots, stems, leaves, and total plant for white spruce seedlings grown at 330, 600, or 1000 ppm $CO_2$. (Higginbotham 1983).

## 3. EFFECTS OF $CO_2$-INDUCED CLIMATIC CHANGE ON TREE SPECIES

Solomon and West (1985) developed a list of variables, data, and ecological responses which must be documented in order to project the effects of $CO_2$-induced climatic change on forest trees. These include a large range of climatic variables, such as frequency of spring frosts, cumulative degree days, and frequency of heat waves, drought, flooding, and intense wind storms. They also included human variables such as land use practices and pollution (including enrichment of atmospheric $CO_2$). These factors may influence trees in all life-cycle stages, or only during specific parts of the life-cycle, and may also have both direct and indirect effects on physiology and growth.

A significant weakness exists in that we know little about how even the economically important tree species of the western boreal forest respond to environmental factors under current $CO_2$ conditions. Extrapolation to the future is impossible without a baseline. Other problems limit our ability to project even on the basis of presently available information. The principal species of the boreal forest have wide natural ranges and occupy many different types of sites. Presumably, significant genetic variation exists among populations; therefore, extrapolation from one population to another is problematic. Acclimation is another problem (Strain et al. 1976). Most species have some potential to maintain physiological processes at or near optimal levels, even though climatic factors may vary. For example, acclimation might allow a seasonal shift in the optimal temperature for photosynthesis such that the optimum will be at or near the seasonal daytime mean temperature. In other words, a single photosynthesis vs. temperature curve does not suffice to define the relationship between these two elements. Since we know nothing about the acclimation potential of the physiological processes of boreal tree species to any environmental factor, we cannot predict what the long-term responses to $CO_2$-induced climatic change will be.

The scanty data available show that white spruce, black spruce [*Picea mariana* (Mill.) BSP], lodgepole pine, and trembling aspen exhibit peak photosynthesis at temperatures near 20°C (Black 1977; Clark 1961; Dykstra 1974; Lawrence and Oechel 1983; and van Zinderen Bakker 1974). This is common for most C3 plants reported in the literature. Increased growing-season air temperatures could conceivably cause the optimum to be exceeded, but it is likely that acclimation and eventual genetic adaptation could compensate for this.

Cold soils are an important limiting factor in northern ecosystems. Global warming is likely to increase soil temperatures, alleviating respiratory and water uptake problems associated with cold rooting media. How important this may be for northern tree species is unknown. Babalola et al. (1968) found sharp reductions in photosynthesis and transpiration of radiata pine (*Pinus radiata* D. Dom.) when soil temperatures decreased from 27 to 10°C. Delucia (1986) found no impact on net photosynthesis of Engelmann spruce (*Picea engelmannii* Engelm.) seedlings for soil temperatures between 10 and 20°C. Similarly, Lawrence and Oechel (1983) found little soil temperature effects on photosynthesis in trembling aspen with rooting zone temperatures ranging from 5 to 25°C.

If warmer growing season temperatures create increased soil moisture stress through increased evapotranspiration, relatively shade tolerant species, such as white and black spruce, will probably experience greater problems than shade intolerant species such as trembling aspen, jack pine, or lodgepole pine. Lopushinsky and Klock (1974) reported that tolerant species tend to have less stomatal control of water loss than intolerant ones. However, this generalization will be influenced by the sensitivity of a particular species to $CO_2$-induced stomatal closure.

Growth of boreal tree species as it relates to particular environmental factors is poorly documented. Growth results from cell division and subsequent cell enlargement. Cell division involves many enzymatic processes which are strongly temperature dependent. Cell enlargement is temperature-influenced, but also strongly depends on the availability of moisture. Maini (1972) showed that height growth of trembling aspen is reduced in the forest-grassland transition zone in Saskatchewan, as compared to predominately forested areas. This is probably due to a reduction in available soil moisture. A similar reduction is noted in the forest-tundra transition zone, probably as a function of low temperatures.

Development of cold hardiness and true dormancy in northern trees may be delayed by increased annual temperatures. Induction of dormancy normally results from shortened photoperiods, but deep dormancy and extensive cold hardiness develop following the onset of below freezing temperatures (Weiser 1970).

## 4. IMPACTS OF EXPECTED CLIMATIC CHANGE ON STRUCTURE AND FUNCTION OF BOREAL ECOSYSTEMS

A fundamental principle of ecosystem function is that all components (plant species, animal species, and the various components of the physical environment) interact with each other. These interactions may take several forms but, because they exist, it can be said that an ecosystem has functional relationships such as for an individual organism (Odum 1969). The structure of an ecosystem is dependent on the size, age, number, and type of interactions which occur between living organisms and the physical environment. Several factors and processes in an ecosystem are likely to be affected by $CO_2$-induced climatic change and by the direct effects of increasing atmospheric $CO_2$. These include competitive relationships, life cycles, natural succession, nutrient cycling, energy flow, and system hydrology.

Competition occurs when different species or different individuals of the same species require the same or similar resource bases, and where some or all of those resources are potentially in short supply. Light, nutrients, and moisture constitute examples of resources commonly competed for by plants. Keen competition between plant species is common in the boreal forest under current conditions. This competition is understood reasonably well and various forest management practices exist for dealing with the problem, where it has a negative effect on economically important tree species. In general, the problem is most significant during the regeneration and establishment phases of the tree life cycle.

All plant species will not react similarly to an enhanced $CO_2$ environment. If, for example, marsh reed grass [Calamagrostis canadensis (Michx.)] responds more to $CO_2$ enrichment than white spruce, competition between the two species will result in a greater advantage to the grass than presently exists. If the tree responds more positively, a currently serious competitive situation may be alleviated.

Kramer (1981) and others have indicated that life-cycle stages (at least in plants) will likely be accelerated in a high $CO_2$ environment. Both vegetative and reproductive maturation will probably occur sooner than under current conditions. This will likely cause the process of natural succession to accelerate. The various seral stages of a succession may remain intact but, their persistence will be reduced. This will have significant, mostly positive, benefits for traditional timber management, but may have negative impacts on game management and some forms of recreation.

Nutrient cycling is typically slow and often limiting in the boreal forest. Much of the nutrient capital is tied up in organic matter on the forest floor. Release of these nutrients is restricted by slow rates of decomposition. Global warming would improve this situation as long as adequate moisture is available. On the other hand, litter quality (C/N and C/P ratios) may be reduced under conditions of higher system productivity which could yield reduced rates of decomposition. If the nutrient cycle is not constrained as suggested above, forest sites will probably be more fertile (a greater percentage of the nutrient pool will be available annually) and the importance of mycorrhizal associations could decrease. Shortened life cycles should increase the rate at which nutrients tied up in living organisms are returned to the forest floor and, ultimately, to the soil, causing further acceleration of nutrient cycling.

## 5. EFFECT ON FOREST GROWTH AND PRODUCTIVITY

Net productivity is known to depend on temperature and precipitation (Lieth 1975), with temperature being the more important control in cool climates and precipitation in hot climates (Bazilevich et al. 1971; Drozdov 1971). The effect of increased temperature on photosynthesis and rate of growth will influence forest productivity and the quality of timber produced from the boreal forest region under $CO_2$-induced climatic change. Productivity models based on the summation of growing season temperature (Kauppi and Posch 1985) may be useful in estimating changes in forest production due to impending climatic change.

With climatic change, much of the existing forest-grassland transition and the southern forest subregions of the boreal forest region may become suitable for agriculture. A study of forest areas with climate similar to that expected from the $CO_2$-induced change will help identify tree species suited to the modified climate scenario. Climate-productivity models may help to update forestry yield tables from existing sites and species.

## 6. EFFECT ON RISK FACTORS

Forestry risk factors such as fire, insects, and diseases will be affected by $CO_2$-induced climatic change. Because of available combustible material, increases in temperature will increase the risk of fire, both in frequency and intensity. These fires will impact the microclimate of boreal subregions. Rouse (1976) reported increases in mean soil temperatures of 60 to 70% after burning of lichen woodland in the Northwest Territories. Such fires also affect the seasonal dynamics of thawing and the soil energy balance.

Temperature and precipitation are factors controlling the incidence and prevalence of forest insects and diseases. Ives (1981) reported weather to be the overriding factor in determining the abundance of 21 forest insects in Manitoba and Saskatchewan. A change in weather patterns under increased $CO_2$ will bring changes in the composition and abundance of insect populations and disease organisms. These changes would impact the present health of our forests and the quality of forestry related resources. As stress develops due to higher temperatures and possibly lower precipitation, trees will be reduced in vigour and become prone to damage by insects and diseases. These changes could affect future timber supplies from the boreal forest.

Energy flow in ecosystems results from feeding by herbivores and carnivores and by decomposition. Strain and Bazzaz (1983) indicated that carbon/nitrogen and carbon/phosphorous ratios in plants are likely to increase in a high $CO_2$ environment. This will probably lead to more herbivory. Defoliating insects may have to eat more to obtain necessary nutrients (Lincoln et al. 1984). Problems such as defoliation by tent caterpillar and spruce budworm, and browsing by snowshoe hares and ungulates, may increase.

## 7. EFFECTS ON FOREST HYDROLOGY

Temperature and precipitation are important factors which influence water yield. A change in either of these factors will determine the amount and regimen of water originating from forest watersheds. Another likely impact will be on the frequency and intensity of drought occurrence due to modified precipitation patterns, and changes in snow accumulation and snowmelt over source areas. However, regional patterns of changes in temperature, precipitation, and soil moisture will determine what impact the Greenhouse Effect will have on local ecosystems, water supplies, and agriculture (Schneider 1987).

System hydrology will be affected by $CO_2$-induced impacts on precipitation. If annual or growing season precipitation decreases or stays the same as at present, and temperatures increase, evapotranspiration demand may become excessive. If precipitation increases, groundwater levels may rise, causing anaerobic conditions in the rooting zone of soils that are now mesic. Such changes would influence plant growth and forest yield.

## 8. FOREST ZONATION AND SHIFT IN BOUNDARIES

All of the processes and factors discussed above will be important throughout the period of climatic change and beyond. In addition, climatic change and impacts will probably cause a northward movement of the boreal forest. A simplified view of the factors controlling current forest boundaries suggests that, in the prairie provinces, the boundary between the predominantly forested area and the forest-grassland transition zone lies parallel to the $2^{o}C$ mean annual temperature isotherm. The northern boundary of the predominantly forested area lies along the $-4^{o}C$ isotherm (Munro 1956; Rowe 1972). Based on predictions of the general circulation model of the Goddard Institute for Space Studies (GISS) for mean annual temperature following a doubling of current $CO_2$ levels, the forest-grassland predominantly forest boundary may shift northward by as much as 700 km. Similarly, the northern boundary of the predominantly forested area will also shift northward. Clearly precipitation, and perhaps other factors, should also be considered, but it appears to be likely that the existing boreal forest will be replaced by grassland, brushland, or temperate forest, and the boreal forest will make significant incursions into the forest-tundra transition zone. After examining the late-Quaternary trends of vegetation history in the Western Interior of Canada, Ritchie (1976) reports that such shifts have occurred in the past.

## 9. FOREST ECONOMIC EFFECTS

The boreal forest is of great importance to the economy of the prairie provinces. Dependence on the boreal forest for commercial and non-commercial amenities will be significantly affected by the impending climatic change. Possible replacement of the southern boreal forest by grassland and a general shift of the forest to the north has economic consequences which need to be studied at length.

Economic impacts within Canada will be related to changes in forestry supplies from other regions of the world as these are also likely to be influenced by future climatic change. An international, econometric model will be needed to study the consequent elasticities of supply and demand, and to determine the net economic benefit/loss of the change.

In addition to changes in commercial timber production, the anticipated climatic change will impact non-market benefits (such as recreational, scenic, and waste receptor) of the boreal forest. As discussed in previous sections, climate warming will also increase the risk and uncertainty associated with growing forestry crops over long periods.

## 10. POLICY IMPLICATIONS OF CLIMATIC CHANGE

Shifts in forestry and agricultural zones will have other important implications for the prairie provinces. The impacts involve many aspects of forestry practices in Canada such as net productivity, species composition and structure of plant communities, forest fires, insect and disease infestations, water supplies, drought, and natural regeneration and restocking. Established forestry industries will also be impacted due to likely shifts in the resource base related to their specific interests.

In order to resolve inherent conflicts, these and many related considerations need to be examined well ahead of the anticipated changes. It is only through timely and careful planning that the impacts of long-term climatic change can be managed so that beneficial effects may be maximized and adverse effects minimized. This planning and assessment will require interdisciplinary cooperation among scientists and resource managers. Fortunately, the change is not sudden but is spread over a number of years, thus giving us enough time to carefully and diligently examine policy alternatives.

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# TOWARDS A FRAMEWORK FOR RESEARCH INITIATIVES INVOLVING THE IMPACTS OF CLIMATIC VARIABILITY AND CHANGE ON WATER RESOURCES IN THE CANADIAN PRAIRIES

by

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## ABSTRACT

This paper provides a review of some of the main knowledge gaps existing in the analysis of climatic variability and change and their impacts on water resources. Gaps are identified in four areas including documenting climatic change and variability, understanding the freshwater components of the carbon cycle, modelling climatic change, and assessing the impacts of climatic change and variability on water resources. The more extensive use of proxy data in documenting climatic change and variability is identified as one opportunity area for research. In the area of modelling climatic change, the need to develop criteria for choosing models for use in impact studies is discussed. Research needs related to assessing the impacts of climatic change and variability on water resources are discussed at some length. Principal needs in this area include the requirement for a better understanding of the complex feedbacks which exist between river runoff, oceans, and the atmosphere; the need for studies which will cover a broader range of hydrological phenomena on the prairies; and the need to communicate this information in an appropriate way to resource managers and policy makers. The paper concludes with a few thoughts on science management and priorities for research organizations in western Canada.

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[1] The views expressed in this paper are those of the author and should not be interpreted as official Atmospheric Environment Service policy.

## 1. INTRODUCTION

The possible impacts of climatic variability and change have received considerable attention in the past few years. However, only a limited amount of attention has been directed to studying the potential impacts of climatic change on water resources in western Canada. There are many examples where improved information on these impacts could lead to significant improvements in planning and managing water resource activities. For example, a better understanding of climatic variability and change could contribute to:

1. The more efficient design of dams, bridges, culverts, and roads, etc., through the use of design statistics based on decadal and longer-term climatic variability and on design strategies which accommodate the possible effects of climatic change;
2. Strategies to optimize economic returns from rivers and reservoirs with potentially reduced or increased flows, increased evaporative losses, and increased demands for irrigation; and
3. Plans for economic development in the rapidly changing Arctic environment, where areas of permafrost are melting and the northern limits of agricultural and forest zones are advancing toward higher latitudes.

This paper outlines the types of studies and research initiatives which are needed to resolve questions related to climatic variability and change and to water resources. In particular, it will identify some questions which need to be addressed and review relevant work from the recent literature and from on-going research at the National Hydrology Research Centre, which could contribute to the resolution of these issues. As might be expected, the research needs and opportunities identified in this report extend beyond the water resources sector. The following questions can be posed concerning climatic variability and change and water resources:

1. How will we be able to detect signals of real climatic change when there is so much noise resulting from the natural variability of the climate?
2. Are the biogeophysical cycles of $CO_2$ and other radiatively active gases, and the role of the hydrosphere in these cycles,

sufficiently understood to enable us to make accurate predictions about their future accumulation in the atmosphere?

3. Can we develop a global climate model which is comprehensive enough to include an adequate simulation of the hydrological cycle and to provide reliable and detailed predictions of the timing and magnitude of climatic change?
4. What are the relationships among climatic change, future water availability, and water use patterns?

## 2. DOCUMENTING CLIMATIC CHANGE AND VARIABILITY

First, let us consider the evidence for climatic change. The opportunities and needs for research in this area are summarized in Table 1. The variability of weather and climate are widely recognized. This variability ranges from day-to-day fluctuations of the weather to the long-term variations and trends which occurred between the ice ages and climatic optima. This leads to the obvious question "When does an alteration in the climate constitute climatic change?" Hare (1985) suggests that climatic change occurs when the differences between successive averaging periods of decades, or possibly centuries, exceed what can be accounted for by noise in the climate signal. This leads to the question concerning an appropriate averaging period for detecting climatic change.

In assessing the onset of climatic change, it will be necessary to choose an averaging period which is sufficiently long to ensure that a significant non-reversible trend is being observed. It is also important to distinguish between local effects and climatic trends. Trends, at individual stations, are often strongly affected by local factors such as urban growth. Regional variations are often compensated for in other regions, so that the average hemispheric or global trend is near zero. Elsasser et al. (1986) summarized a number of studies which demonstrate that the atmosphere typically cools in one area while it is warming in another. A global temperature trend becomes difficult to quantify when the net warming occurs in a data-rich area such as North America and the net cooling occurs in a data-sparse area such as the Pacific Ocean. In this situation, adding together all the observation

Table 1. Opportunities and needs for research related to climatic change and variability.

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NEEDS:

1. Understanding the nature and causes of climatic variability.
2. Reliable indicators of climatic change.

OPPORTUNITIES:

1. Develop improved areal averages of precipitation
2. Develop a basis for distinguishing between climatic variability and change
3. Use biogeophysical indicators to:
   a. Extend instrumental record
   b. Identify best indicators of climatic change
   c. Determine limits of normal climatic variability
   d. Understand teleconnections and feedbacks
   e. Understand linkages between climatic change and other environmental changes
   f. Design and implement monitoring programs

points from both regions, without any consideration of the area represented by each station, would indicate that global warming was taking place, even if the net temperature change could be zero. Hence, it is important to develop observational programs with a spatially uniform distribution of observation sites or to develop procedures for analyzing the data so that appropriate weights can be assigned to the observations from the data-sparse regions.

The calculation of areal averages of precipitation is particularly difficult since precipitation is produced by both stratiform and convective clouds. As a result, the scale of the events producing significant precipitation amounts can vary from several kilometers to several hundred kilometers. This variability affects the reliability of inferences made about precipitation patterns. Raddatz (1987) found that the representativeness of rainfall measurements inferred from a rain gauge in prairie terrain near Winnipeg decreased significantly with distance. For winter precipitation, there is a need to standardize snowfall data based on the types of snow gauges used. This is particularly important for analyses involving data collected in the USA, the USSR, or other countries which have snow gauges differing from those used in Canada. The procedures for standardizing snowfall data do not appear to be well known and seem to be rarely applied.

Time variations in climatic parameters are also significant. The onset of climatic optima and ice ages apparently occurred at intervals of approximately 100 to 200 thousand years (Elsasser et al. 1986). Instrumental records are limited in terms of their length and the number of sites for which long-term records are available. Records of temperature and precipitation over lakes or on mountain slopes are rarely available. However, a considerable amount of information about past climates can be inferred from cores taken from alpine and polar glaciers, lake sediments, tree rings, and other types of proxy data.

Ice core samples can provide information on past precipitation amounts. Dr. G. Holdsworth of the National Hydrology Research Institute is analyzing an ice core which he retrieved in 1984 from the glacier on Mount Logan. This core provides a 300-year history of precipitation amounts and temperatures on the top of the mountain. Based on this precipitation record, Holdsworth (1987) has found that from 1893 to 1963 annual precipitation amounts on Mount Logan appear to correlate with the winter snowfall amounts measured at 22 stations in the USSR. Further work is needed to confirm these relationships and to determine the physical linkages which could account for this correlation.

Tree rings are another source of proxy data. Parker and Geast (1987) used tree ring analysis to infer August temperature patterns across Canada on a yearly basis back to 1800. Based on the utility of these and other studies, it is concluded that there is a need to expand this type of research. A consolidated database must be developed which will allow for the intercomparison of the climatic records derived from the various types of proxy climate data.

The results of the analysis of proxy data demonstrates the need for a better understanding of the processes which lead to climatic variability and teleconnections between different regions. In addition, new statistical procedures and more extensive climate records are needed to determine if trends observed in the instrumental records are related to teleconnections or result from other factors. There are limitations in relying exclusively on the instrumental record. Many of the processes causing climatic variability operate on time scales longer than 100 years; consequently, they cannot be identified from an analysis of the instrumental record. Furthermore, some of the most dramatic and sudden changes occur in areas where few observations are made. For example, according to Bassinger (1987), trees existed on the east side of Axel Heiberg Island 45 million years ago. These trees included dawn redwood and swamp cypress, both characteristic of climates similar to those of southern Georgia where the mean annual temperature is 20°C. At present, the mean annual temperature on Axel Heiberg Island, where these fossils are located, is approximately -19.7°C. Results from paleoecological data, exhibited at the Tyrrel Museum, in Drumheller, Alberta, also suggest that warm temperatures existed in the Arctic 20 million years ago. These exhibits indicate that the boreal forest zone was much narrower and further north at that time. Although these examples indicate that the largest climatic changes occurred north of 65°N, Canada's climate network at these latitudes is sparse in comparison with the rest of the country.

There is a need to develop a monitoring capability which will indicate where and when the first irrefutable signals of a climatic warming are taking place. Some elements of an early detection system should be based on or include:

1. Studies and analyses to identify areas likely to be affected first and most significantly by climatic change;
2. Monitoring programs in the most sensitive areas;
3. Analytical techniques to facilitate the differentiation between local and regional climatic variability, and long-term climatic change; and
4. Extensive use of biogeophysical indicators of climatic change.

The last point is an important opportunity for Canadian environmental monitoring programs. Many biogeophysical parameters indicate the integrated effects of temperature and precipitation changes over a large area on a medium to long time scale. In particular, stream flow, sedimentation rates, glacier movement, vegetation cover, and lake freeze-up and thaw are all affected by temperature, precipitation, and other climatic factors. By monitoring the temporal variations and changes in these parameters at a number of sites, it may be possible to detect climatic changes before it is clearly identifiable in the temperature and precipitation records. For example, changes in temperature may lead to reductions in the size of mountain glaciers; by monitoring changes in glacier size it may be possible to infer changes in climate. Young and Ommanney (1984) reported that significant reductions occurred in the size of mountain glaciers during the first part of the twentieth century. This pattern could be expected to result from warmer summers and less winter precipitation.

Anderson (1987) assessed the feasibility of using lake ice conditions to monitor climatic change. He found that changes in air temperature were correlated with changes in the ice regime, provided that air temperature was the only environmental parameter which was changing (i.e., snowfall amounts were constant). The strength of this correlation varied for individual lakes. Other parameters seem to offer less hope. For example, Klemes (1985) concluded, for streamflow, even a rather profound climatic change could not be readily identified as such and distinguished from the normal short-term variability.

Table 2 summarizes biogeophysical parameters which could give an early detection of climatic change and outlines the potential usefulness of each parameter. This table is based largely on a report by the US Department of Energy (1985). Before setting up an extensive climatic change monitoring program, the utility and sensitivity of these parameters to climatic change should be analyzed. Once the sensitivities are known, it would be possible to supplement the monitoring program with sites where a number of viable ecological parameters can be monitored.

## 3. UNDERSTANDING THE CARBON CYCLE

The underlying cause of the anticipated climatic change is the buildup of carbon dioxide and other radiatively active gases in the atmosphere. Anthropogenic activities have resulted in increasing concentrations of $CO_2$ from the burning of fossil fuels, NOx from automobiles, and freons and organics from various industrial processes. These are only a few of the many sources of these gases. Although the carbon cycle has been studied for many years, it still poses many unresolved questions. The role of the biosphere is not fully understood. Further, the significance of converting rainforests to agricultural land in the buildup of atmospheric $CO_2$ levels is still contested. A number of studies have dealt with the relative importance of oceans in the carbon cycle. One of the uncertain aspects relating to the role of oceans involves their strong latitudinal and seasonal variations in biological activity.

Henderson-Sellers (1987) argued that water vapour is also an important radiatively active gas. She points out that the Goddard Institute for Space Studies (GISS) and Geophysical Fluid Dynamics Laboratory (GFDL) models predict a decrease in cloud cover while studies of historical cloud observations have shown that there is more cloudiness in warmer years. It appears that water vapour inputs to the atmosphere will lead to cloud formation, and in turn these clouds will limit the extent of warming due to

Table 2. Biogeophysical parameters which could give an early signal of a $CO_2$-induced climatic change.

| Potential Indicator | Problems | Overall Potential |
|---|---|---|
| - Radiative balance of the atmosphere | - Too much natural variability<br>- Absorption properties of atmospheric gases not well understood | - Low |
| - Areal averaged surface temperatures | - Large spatial variability<br>- Ocean thermal effects and other forcing factors are difficult to assess<br>- Data networks sparse in the most sensitive areas | - Good (no conclusive evidence of $CO_2$ warming) |
| - Sea level changes | - Lack of global coverage<br>- Data sets are short term<br>- Small signal must be separated from noisy data | - Medium (present trends consistent with $CO_2$ warming) |
| - Precipitation patterns | - Long-term natural fluctuations occur on continental scale<br>- Natural processes and effects must be better understood<br>- Feedback processes may amplify or reduce changes | - Low to medium |
| - Snow cover, floating ice, river run-off | - High spatial variability from year to year<br>- Large natural variability | - Low to medium (fast response to climatic change) |
| - Ground ice, glaciers and ice sheets | - Significance of effects (particularly for permafrost because effects depend on the time of warming) | - Medium (slow response to climatic change |
| - Vegetation | - In some cases, difficult to separate among effects leading to changes (soil type vs. $CO_2$) | - Medium (anticipated slow response to climatic change in the Arctic) |

the Greenhouse Effect. However, the potential impacts of anthropogenic activities on water vapour content do not appear to have been documented in the context of climatic change.

In spite of the work done on the carbon cycle, the role of inland waters has not been extensively documented. Canada's freshwaters may play a significant role in this cycle. The surface area of freshwater lakes in Canada is 755 180 $km^2$. Since, even in summer, the water in most of these lakes is cold, they have considerable potential to withdraw $CO_2$ from the atmosphere. If these lakes become ice-free for long periods of the year, this could significantly increase the hydrosphere's ability to take up $CO_2$ from the atmosphere.

Sediment transport may also be important. On a world-wide basis, 13 695 x $10^6$ metric tonnes of sediment are transported to the oceans annually. According to Kempe (1979), rivers transport 643 x $10^{15}$ g of carbon into the oceans with 70% of this being in the form of bicarbonate ($HCO_3^-$) ions. In Canada, 300 x $10^6$ metric tonnes of sediment (2.1% of the world's total) are transported on an annual basis. This quantity represents a significant movement of carbon from the terrestrial system to the world ocean.

The Arctic and Antarctic oceans will have greater potential for withdrawing $CO_2$ from the atmosphere under a warmer climate. However, withdrawal rates of $CO_2$ under the present climate are not well defined. More research is needed to determine the present and possible future rates of $CO_2$ withdrawal by the Arctic Ocean and by the northern lakes. Table 3 summarizes the opportunities and needs for research related to the carbon and freshwater cycle.

## 4. MODELLING CLIMATIC CHANGE

A number of Global Circulation Models (GCMs) have been developed and used to investigate the impacts on climate of 2 x $CO_2$ or 4 x $CO_2$ concentrations. Generally, these models generate output fields of temperature and precipitation, as well as a number of other parameters. The temperature fields of these models have received the most attention. The models are becoming increasingly sophisticated and contain parameterizations for a number

Table 3. Research needs and opportunities related to improving the understanding of water's role in the carbon cycle.

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NEED:

To gain a comprehensive understanding of the role of fresh water in the carbon cycle and to obtain more accurate projections of the rate at which $CO_2$ and other radiatively active (RA) gases will accumulate in the atmosphere.

OPPORTUNITIES:

To improve our understanding of the roles of:

1. Rivers and inland lakes in absorbing, transporting, and storing $CO_2$ and carbon-rich sediments or RA gases.
2. The Arctic and the Antarctic oceans in withdrawing $CO_2$ and other RA gases from the atmosphere.

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of physical processes including land-atmosphere interactions. However, increased sophistication need not lead to more reliable results.

The GFDL model appears to be a case in point. Early versions of the GFDL model predicted significant warmings associated with $CO_2$ increases in the Arctic and the Antarctic (Manabe and Stouffer 1980). Figure 1 illustrates the modelled temperature distribution for the summer months over North America. Later versions of the model, in which cloud cover was allowed to vary, led to the summer temperature fields shown in Figure 2 (Manabe and Wetherald 1987).

A preliminary comparison suggests that the later results may be less realistic for the Canadian prairies than the earlier results. For southern Manitoba in June, July, and August, the new GFDL model predicts average temperatures $9^{0}C$ higher than at present (Figure 2). At Morris, Manitoba, this would lead to a mean daily temperature of $27.6^{0}C$ for the three summer months. If the present diurnal temperature variations were maintained, it would result in a summer mean daily maxima of $34.5^{0}C$ and mean daily minima of $20.7^{0}C$. If precipitation remained unaltered for these months, Morris, Manitoba, would have a summer climate similar to that of the towns on the Oklahoma-Texas border.

Global Circulation Models should also be capable of reproducing known atmospheric behaviours. Scientists involved in impact work have experimented with various ways of dealing with anomalies between the model's predicted 1 x $CO_2$ climate and the real climate of the atmosphere. The reliability of temperature and precipitation fields for 2 x $CO_2$ scenarios from a model which cannot reliably produce the current climate should be questioned.

Improved linkages must be developed between parameters of hydrometeorological and hydrological processes and Global Circulation Models. Because of the procedures used in "lumped" hydrological models designed for individual basins or watersheds, it is difficult to include their hydrological processes in a Global Circulation Model. For example, it should be possible to include the physics of land use changes, such as the conversion of forests or wetlands to agricultural lands and the consequent changes in evapotranspiration, in the computations of long-term projections of climate.

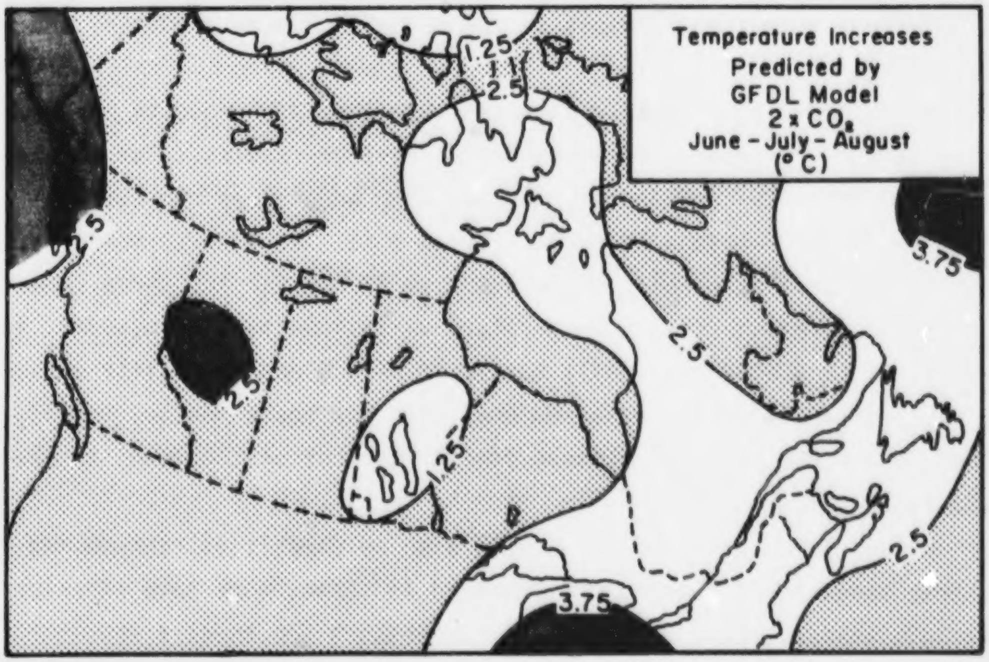
Temperature Increases
Predicted by
GFDL Model
2 x CO₂
June - July - August
(° C)
1.25
2.5
2.5
2.5
1.25
1
2.5
3.75
3.75
2.5

Figure 1. Warming ($^{o}C$) expected to result over North America during June, July, and August from a doubling of $CO_2$ (Manabe and Stouffer 1980).

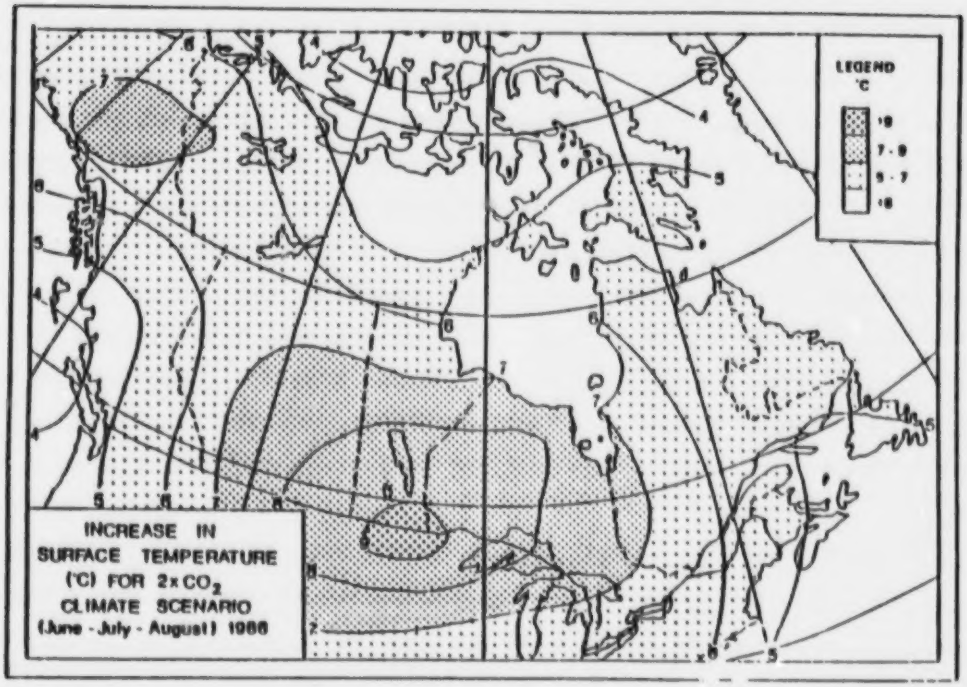
LEGEND
°C
>9
7 - 9
5 - 7
<5
INCREASE IN SURFACE TEMPERATURE (°C) FOR 2xCO$_2$ CLIMATE SCENARIO
(June - July - August) 1986

Figure 2. Warming (°C) expected to result over North America during June, July, and August from a doubling of $CO_2$ (Manabe and Wetherald 1987).

It may be necessary to develop sub-grid scale models of land processes which can then be efficiently integrated with a GCM. Finally, it is important to better understand how parameterizations of the hydrological processes affect the results from a GCM.

Hydrological models tend to be empirical or statistical in nature. As Klemes (1985) pointed out, hydrologists often substitute for the lack of physical knowledge by calibrating these models. To do this, they develop statistical relationships specific to the basin. Hydrological models must become more physically based if they are to provide an effective interface between the land and atmosphere processes. A better understanding of feedback between surfaces such as lakes, rivers, forests, agricultural lands, and the atmosphere, through evaporation and precipitation processes, is required. Studies in highly instrumented watersheds under different climatic conditions are needed to fill this knowledge gap. Once these feedbacks are understood, they can be incorporated into hydrological parameterizations for use in General Circulation Models. The transferability of existing hydrological models to climate problems should be documented to determine which models might best serve for future parameterization initiatives.

Another problem in GCM outputs arises from the use of a set of deterministic equations to reproduce some "equilibrium" or average state for a highly non-linear system such as the atmosphere. While it may be possible to develop better parameterizations of the various physical processes involved, there will always be uncertainty arising from: (1) the inherent randomness of atmospheric process, (2) our lack of understanding about feedback processes, and (3) our inability to define the initial state of the atmosphere with complete certainty. The practice of using monthly and seasonal averages alleviates this problem to some extent. However, it is important that GCMs be used to generate information on year-to-year and day-to-day temperature and precipitation variability in addition to the presently available average values. To fully assess the significance of climatic change scenarios on resources, information is needed on the increased or decreased inter-annual variabilities (both in space and time) of precipitation amounts and temperatures. Currently, climate impact studies have been based on the assumption that, although the mean will change, climatic variability will remain constant. These research opportunities and those identified in the foregoing paragraphs are summarized in Table 4.

## 5. ASSESSING THE IMPACTS OF CLIMATIC CHANGE ON WATER RESOURCES

### 5.1 SELECTING A GENERAL CIRCULATION MODEL SCENARIO

A major opportunity area for climatic change research involves assessing the impacts of climatic change on water resources (Table 5). Studies are needed to determine which climate scenarios are most realistic for western Canada. While all models show a warming trend on the prairies and in the Arctic, their similarity ends at that point. Some models indicate decreases in soil moisture on the prairies, some show no significant change, and some even show soil moisture increases. New developments in GCMs must be analyzed and an on-going assessment of model outputs undertaken to ensure that appropriate models are used in water resource impact studies.

Some authors have reviewed models from the perspective of which parameters are included or not included. While this is important, GCMs should be judged primarily on their overall performance and ability to reproduce known atmospheric characteristics and behaviour. In particular, the following criteria are proposed for assessing model outputs:

1. Can the model reproduce the present climate?
2. Does the model reproduce the structural components of the climate?
3. Are the predicted changes physically possible given the changes in environmental conditions (e.g., increased $CO_2$ levels)?
4. Does the model reproduce known atmospheric behaviour teleconnections and feedback effects?

The feedback processes among land, ocean, and atmospheric processes are often quite complex. However, an understanding of these interactions is essential for assessing the impacts of climatic change on water resources and for understanding the limitations of the climatic change scenarios produced by GCMs.

Table 4. Research needs and opportunities related to the more effective integration of general circulation and hydrological models.

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NEEDS:

1. To more effectively incorporate hydrological processes into GCMs.
2. To make GCM outputs more responsive to the information needs of water managers.

OPPORTUNITIES:

1. Quantification and modelling of land/ocean/atmosphere interactions on regional and global scales.
2. Improved hydroclimatological inputs.
3. Computationally simple, physically accurate parameterizations of the hydrological cycle.
4. Procedures for deriving GCM outputs for medium-sized watersheds.
5. Assessment of model outputs:
    a. All significant processes included?
    b. Global and regional changes realistic?
    c. Ability to reproduce structural components of the climate?
    d. Feedbacks reproduced?

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Table 5. Research opportunities and needs related to the assessment of the impacts of climatic change on water resources

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NEED:

To define and, where possible, quantify the possible impacts of climatic change on water resources.

OPPORTUNITIES:

1. Assess variability of hydrological parameters in historical and pre-historical times.
2. Review the various climatic change scenarios and select two or three which are most realistic.
3. Study the ways in which the most proable climatic change scenarios will affect the future water supplies from storm run-off, snow melt, glacier melt.
4. Study the impacts of climatic change scenarios on groundwater supplies.
5. Study the changes in hydroclimatological parameters such as the seasonal distribution of precipitation, the characteristics of severe rainstorms, maximum rainfall intensities, and regional and local wind patterns during winter which will occur under different climatic change regimes.
6. Assess the impacts of the anticipated changes in hydroclimatological parameters on agricultural and hydrological droughts, hydrological design criteria, water supply patterns, and hydrological processes, etc.
7. Assess the effects of climatic change on water use patterns (e.g., more demand for irrigation) and the economic aspects of water use.
8. Assess the increased risk to public safety due to more frequent hazards such as landslides, floods, tornadoes.
9. Assess the impacts of climatic change on the Arctic, including permafrost and sea ice.
10. Provide policy advice and design information for water resource planners based on probable climatic change scenarios.

## 5.2 RECOGNIZING PRECIPITATION/RUN-OFF/OCEAN STRATIFICATION FEEDBACK EFFECTS

Land and ocean processes influence energy and moisture transfers to the atmosphere. Following is an elaboration on one important process which, in the author's view, merits further research. Zhao and McBean (1986) found that the energy transfer to the atmosphere over the northeastern Pacific Ocean is greatest in the winter months when the cold air flows over the warm waters of the Kuroshio Current. They also reported that large heat fluxes occurred in 1962 and 1963 indicating that cold air advection was present even though sea surface temperature anomalies were small.

Lazier (1980) indicated that heat losses from the North Atlantic Ocean are large when deep convection is taking place in the ocean. During "normal" years, the depth of convection in the ocean in the winter is largely a function of density stratification and usually reaches depths of 400 to 1000 m. He also found that when pulses of low-salinity water entered the North Atlantic, as occurred from 1967 to 1970, the vertical stratification of the ocean effectively limited the depth of convection to the upper 200 m. It appears that heat loss to the atmosphere is greatest when cold air advection is greatest and when the water column is least stable. Lazier also found that salinity was at a minimum during the summer when outflows of water from the Arctic were greatest. This relationship suggests that run-off and ice melt in the Arctic are important factors in determining salinity values in the upper levels of the North Atlantic Ocean.

The question then arises "What leads to the invasion of lower-salinity water into the North Atlantic Ocean?" If we consider the Arctic Basin, we find from Figure 3 that inflows from North America were well above average between 1964 and 1966. The runoff in each of these years was higher than the annual runoff recorded in any year between 1930 and 1963. It is reasonable to assume a time lag between the emergence of the low-salinity water from the Arctic Ocean and its appearance in Davis Strait and subsequently the North Atlantic. These large inflows could have accounted for the observed invasion of low-salinity water in the North Atlantic between 1967 and 1970.

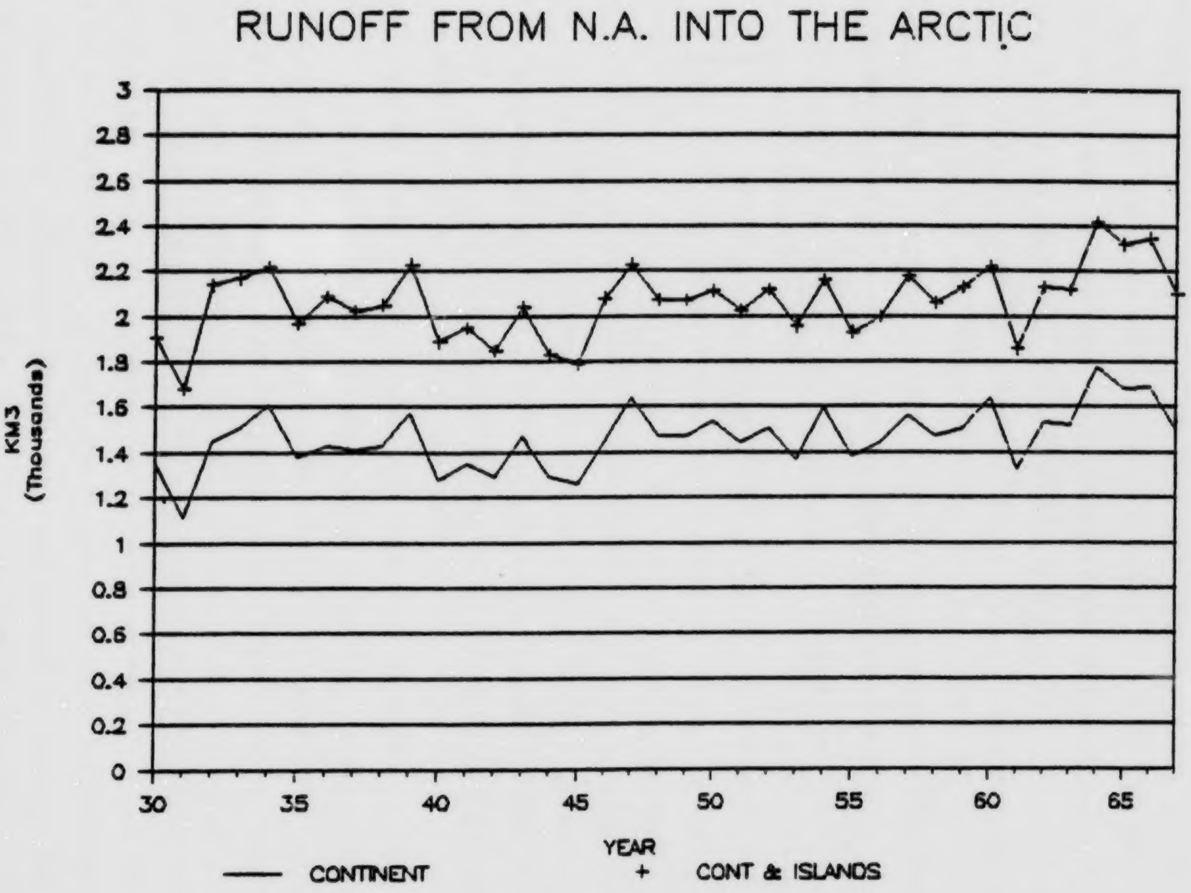

Figure 3. Runoff from the North American continent and into the Arctic basin (after data from UNESCO 1978).

It is possible that the large heat fluxes over the Kuroshiro Current in 1962 and 1963 may have been associated with deep convection in the ocean or some other related ocean phenomenon. These large fluxes occurred in a period of below normal fresh water inflow into the eastern Pacific from the Asian continent and its islands. With less fresh water entering the coastal current, deeper convection would likely have occurred in and around the Kuroshiro Current. If these relationships are confirmed by a more thorough analysis, then an important feedback mechanism among precipitation over continents, runoff, pulses of low salinity water into the oceans, vertical stability in water columns, and energy transfers into the atmosphere has been identified. These hypothesized relationships, summarized in **Figure 4**, could also have predictive value.

### 5.3 APPLYING GCM SCENARIOS TO WATER RESOURCE QUESTIONS

Once a model or models have been chosen, the next step is to assess how the changes will affect water demand and water supply. Some recent models, for example Manabe and Wetherald's (1987) GFDL model, have produced run-off estimates. Because of the large difference in scale between the model and prairie watersheds, it is not surprising to find that in the prairies the results do not relate well with expected values.

As a first step in assessing the probable effects of a GCM scenario on water supply, one must determine the relationships among temperature, precipitation, and streamflow. Various approaches have been used. Langbein et al. (1949) developed correlations between streamflow and precipitation for a large number of USA rivers under different mean temperatures. Various researchers have taken the predicted changes in temperature and precipitation values from climatic change scenarios and applied them to these curves in order to estimate changes in streamflows. However, as Karl and Riebsame (1987) demonstrated, this approach is not entirely satisfactory as it fails to consider the effects of insolation. It may substantially overestimate the effects of temperature change on evaporation within a basin. Based on their research, they concluded that increases in precipitation of a few percent would offset the effects of the $1^{o}$ to $4^{o}C$ warming expected in the next century.

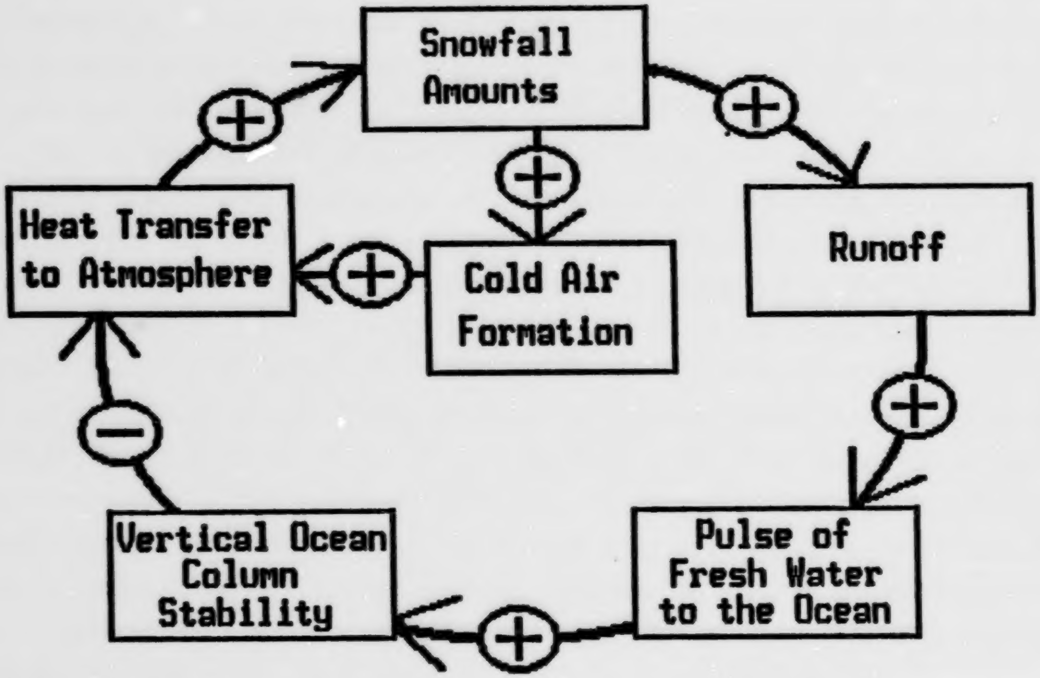
Snowfall Amounts
+
Runoff
+
Pulse of Fresh Water to the Ocean
+
Vertical Ocean Column Stability
−
Heat Transfer to Atmosphere
+
+
Cold Air Formation
+

Figure 4. Possible feedback mechanism linking precipitation, runoff, ocean stability, and heat fluxes.

The effects of using deterministic equations to predict climate impacts have been assessed by Klemes (1985). He used estimates of run-off, generated from several different models, to look at the possible influences of changes in precipitation and potential evaporation on the design of dams. He found that run-off curves derived from these run-off scenarios reproduced each other in terms of the timing and the relative magnitude of predicted flows. While the overall annual flow estimates were reasonable, Klemes was skeptical about individual peaks. He concluded that separate rather than global testing was required to examine the adequacy of the structural components of these models. He attributed this common behaviour to the need for making unverified assumptions about inputs to hydrological models to fill in for gaps in factual knowledge. These assumptions, though logical, may sometimes be wrong.

Cohen (1986a) and Gleik (1987) have used a more physical approach, based on a water budget model, to calculate Net Basin Supply. Cohen applied the Thornthwaite model and a lake evaporation model to estimate runoff for individual watersheds in the Great Lakes Basin from monthly values of temperature and precipitation. He then used temperature and precipitation values from the outputs of the GISS and GFDL models for the 2 x $CO_2$ scenario to derive new runoff and evaporation estimates. The results of his study indicate that the Net Basin Supply in the Great Lakes will decrease. This finding has significant economic and policy implications in terms of greater demands for municipal water and hydroelectric power production. It appears that the water balance model holds more hope than other approaches for producing reasonable water availability scenarios on the prairies.

Assessing the impacts of climatic change on water resources is complex and should include both short- and long-term effects. Figure 5 shows the factors which contribute to runoff in the North Saskatchewan River at Lea Park near the Alberta-Saskatchewan border. It is partly based on the work of Young (1977), who estimated that approximately 10% of the flow crossing the Alberta-Saskatchewan border comes from glaciers.

If warmer temperatures prevail for a number of decades, it could lead to the retreat and eventual disappearance of alpine glaciers which contribute to the base flow of the North Saskatchewan River. In turn,

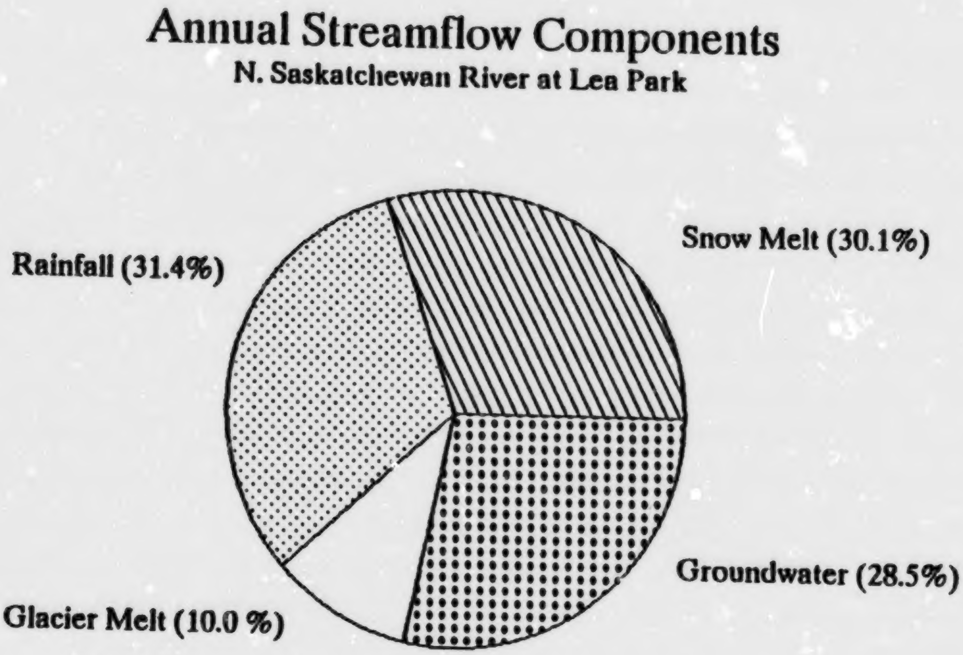

Figure 5. Factors which contribute to river flow in the North Saskatchewan River at Lea Park.

this would result in a significant reduction in glacial run-off. According to the monthly estimates for the factors contributing to flow in the North Saskatchewan at Lea Park, almost 13% of the total flow during June, July, and August is derived from glaciers. Combined with the possibility of lower rainfall amounts on the prairies, eliminating glacial melt-water could seriously reduce the flows of the North Saskatchewan during the summers and falls of the next century.

Mass balance models of glaciers have been developed. By carrying out sensitivity studies with these models, it should be possible to determine the effects of $CO_2$ induced changes in precipitation and temperature on alpine glaciers. Ohmura (1987) has used temperature and precipitation at the equilibrium line altitude (ELA) to compare 55 alpine glaciers around the world. With additional work, his findings could be developed into a model to determine if an alpine glacier is currently growing or shrinking and to predict the effect of changes in temperature and precipitation at the ELA.

Sensitivity studies using hydrological models could also provide an understanding of how streamflows respond to changes in climate. Areas where sensitivity studies could provide new insights into the possible effects of climatic change include mountain watershed models, in which snowmelt is a very important factor, and sediment models in which both the direct effects of altered run-off patterns and the impacts of altered lands use patterns could be assessed. However, the value of these studies will be limited by the adequacy of the models to simulate the physical processes of the hydrosphere.

Another aspect to consider, in assessing the impacts of climatic change on water resources, is the increased demands for water which will likely arise as a result of warmer temperatures. Cohen (1986b) studied the possible effects of variations in temperature and potential evaporation on water demands from the Great Lakes Basin. He reported that, historically, warmer summer temperatures combined with low precipitation have resulted in increases in municipal pumpage. It is probable that in southern Alberta and Saskatchewan, demands for irrigation water will also increase with increasing temperatures and evapotranspiration rates. These demands for water will often be greatest at times of minimum supply.

The implications of climatic change scenarios on extreme weather events have not been fully explored. With a warming of the near surface layers and a cooling of the middle and upper troposphere, we should expect more atmospheric instability. This instability may be accompanied by more severe convective storms. In Alberta, where there is a relatively high frequency of hail and, more recently an increased awareness of the potential for severe tornadoes and urban floods, this should be an important concern. The possibility of increased frequencies of avalanches and landslides is also a concern for western Canada.

To effectively alert politicians and policy makers about the impacts of climatic change on water resources, we must develop the capability of assessing the economic impacts. A reliable and comprehensive socio-economic model is needed to facilitate the assessment of future, climate-induced changes in water supply demand patterns. Models of economic impact must include agriculture and forestry sectors and include both regional and national economic linkages. Acres International (1987), under contract to Environment Canada, has developed one such model. Other models are under development including one for the Saskatchewan portion of the South Saskatchewan River Basin. By incorporating the expected economic changes, it should be possible to delineate optimum water management strategies for different climatic change scenarios.

## 5.4 OTHER CONSIDERATIONS AFFECTING THE ASSESSMENT OF CLIMATIC CHANGE IMPACTS ON WATER RESOURCES

In the author's view, there is a need to consider how information on climatic change should be incorporated into decision making. With the meteorological community, there has been a tendency to generate climatic change scenarios and present them to resource managers with little or no quantitative information about the uncertainty associated with the scenarios. Further, there is often inadequate guidance regarding the ways in which these scenarios should be used. Climatologists should work more closely with resource agencies to assist in selecting appropriate climatic change scenarios and in evaluating the potential effects of these scenarios on resources.

Scenarios of climatic change could also be considered in the development of policy initiatives. For example, one emerging initiative related to Canada's new water policy involves water pricing. To the author's knowledge, no one has assessed the extent to which the water pricing policy could place undue stress on certain water users in western Canada, given the various scenarios of altered supply and demand patterns likely to accompany climatic change.

Before concluding this review, a few words should be said about the characteristics of the research climate needed to facilitate climatic change studies. At the National Hydrology Research Centre, research initiatives are often slowed, and sometimes brought to a halt, because the appropriate data are not available. Interagency and international cooperation and free data exchange between western and eastern nations are essential ingredients for successful climatic change studies. There are a number of other factors which could also facilitate climatic change studies (Table 6).

In the author's view, it is important for users to have realistic expectations about the results which can be expected from climatic change research now and in the future. Users must be aware that researchers can provide scenarios, but not predictions, of future climates for a particular region. Furthermore, this is likely to be the case for the next 5 to 10 years. Accordingly, policy makers and resource managers should avoid making irreversible decisions on the basis of outputs from the current Global Circulation Models.

## 6. SUMMARY

There are many opportunities for research aimed at elaborating on the relationships between potential climatic change and water resources. However, it appears that some problems are fundamental while others are more short term. The following list identifies some priority problems which could be appropriately addressed in western Canada.

1. Extensions of the instrumental record through the analysis of proxy data, and the interpretation of these analyses to obtain a better understanding of feedback processes and teleconnections which exist in the atmosphere.

Table 6. Management and administrative policies which could facilitate climatic change research.

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1. A multi-disciplinary approach is essential.
2. Interactions among experimental scientists, modellers, and climatologists should be encouraged.
3. International collaboration and data exchanges should be encouraged and facilitated.
4. Governments and funding agencies should recognize that continuity of funding is essential for climatic change research.
5. The highest professional ethics and judgement must be exercised by scientists who interact with policy makers.
6. In an era of limited resources, coordination of research efforts at national and international levels is essential.
7. Periodic reviews of various aspects of the climatic change problem are required.

2. Assessments of the consequences of various climate scenarios for water supply and demand patterns in western Canada, and for the economy of the western provinces.
3. Development of hydrological models and hydrometeorological parameterizations for incorporation into Global Circulation Models and for use in assessing the potential impacts on water resources of various climatic change scenarios.
4. Studies of feedback processes among precipitation, the land component of the hydrological cycle, the biosphere, the oceans, and the atmosphere.

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# POTENTIAL IMPACT OF GREENHOUSE GASES ON URBAN TEMPERATURES AND ITS IMPLICATION TO GAS REQUIREMENT FOR SPACE HEATING IN CALGARY

by

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## ABSTRACT

The intensity of the heat island typical for a given city is defined by the mean annual temperature and precipitation of the region in which the city is located and by the city's population. A doubling of atmospheric greenhouse gases could reduce this intensity by up to 20%, but because of the upward pressure exerted by population growth, the projected decrease for Calgary is only about 7%. Thus, urban temperatures in the city will experience virtually the same increase as projected for the grid in which Calgary is located. Eighty-four percent of the energy consumption for space heating is directly attributable to the average temperature of the city; 12% is dependent on temperature variability and the remaining 4% is the "error" term. Under a 2 x $CO_2$ scenario, gas demand for space heating per capita of population could drop between 24 and 33% below the current level. However, energy use for cooling during the summer is projected to rise by between 5 and 8%.

# ACKNOWLEDGMENT

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## 1. INTRODUCTION

There is overwhelming evidence that cities modify local climates. Such modification is both internal and external. Internal modification is caused primarily by the release of waste heat into the ambient atmosphere over the city from numerous urban sources. Atmospheric pollution and a complex urban fabric and geometry combine to regulate the city's energy and moisture balances. This results in a climate with temperature, wind, humidity, and precipitation fields significantly different, on the average, from those of the rural surroundings. External modifications stem from the thermal and pollution plumes which are carried from the city into the suburbs and the downwind rural communities. These plumes alter the heat and water balances in those communities resulting in events such as a higher frequency of showers and thunderstorms than experienced in their upwind equivalent (Claasen 1970; Huff and Changnon 1973). It follows that any factors which promote or inhibit the ability of a city to influence either its own climate or the external one should evoke significant scientific and practical interest. A $CO_2$-induced climatic change is seen as one such factor.

To arrive at realistic values for temperature in urban areas under the 2 x $CO_2$ scenario, a scenario that includes not only the impact of $CO_2$ enrichment, but also the effect of other radiatively active or greenhouse gases, it is necessary to evaluate the impact of the gases on the urban heat islands. The size of the heat island (the difference between city temperature and its rural envelope) could then be used to adjust the temperature projected for the geographical grid in which the city is located to obtain "true" estimates of urban temperatures. Based on the revised temperature, estimates of the energy requirement for space heating under a changed climate may be derived for the city.

This paper has two objectives. Firstly, it seeks to demonstrate how a change in climate, driven by a doubling of $CO_2$ and other greenhouse gases, would affect climates in urban areas especially in the context of the region in which they are located. Secondly, it evaluates the potential impact of the change on the consumption of natural gas in the city of Calgary.

Two General Circulation Models (GCMs), one developed by the Geophysical Fluid Dynamics Laboratory (GFDL) and the other by the Goddard

Institute for Space Studies (GISS), are widely used in predicting the climatic impact of $CO_2$ enrichment. Both models project a general, latitudinally sensitive, upward revision in temperature and more selective changes in precipitation. Although the two scenarios vary in detail, they are often viewed as convergent. In Canada, studies have been or are being done on the potential impact of 2 x $CO_2$ on agriculture, forestry, water resources, and energy (Environment Canada 1987). This study is a first attempt at evaluating the effect of climatic change on urban climates in general, and its implication on the future use of gas in homes and offices in Calgary in particular.

The urban heat island phenomenon is one measure of urban climates used to represent the impact of a city on its own climate. It is also the one variable for which there is a fair amount of globally archived data. Therefore, it is convenient to use $\Delta T_{u-r}$, the heat island intensity, as the criterion to assess the response of urban areas to the 2 x $CO_2$ scenario.

## 2. METHODOLOGY

### 2.1 CHOICE OF VARIABLES

The choice of predictor variables used for assessing future strengths of urban heat islands was based on a survey of the literature on both urban climate and climatic change. The variables chosen were: city population, mean annual regional temperature, and precipitation.

City size plays a significant role in urban climates (Petterssen 1969). When groups of buildings merge to form towns and cities, they generate what Lockwood (1979) described as a 'climatological dome' with a well-defined set of anomalies; an urban heat island being one of them. As cities grow so do their heat islands. Oke (1973) found a relationship between maximum urban heat island intensities and population. Nkemdirim and Truch (1978) found that, over a 10-year period, the mean intensity of Calgary's heat island increased by about 0.3°C for every 100 000 increase in population.

Urban heat islands are most intense during the coldest months. This was well demonstrated by Chandler (1962) for the mid-latitudes and by

Jauregui (1969) for the tropics. The primary reason for this pattern is the increased use of fossil fuel for space heating and transportation during the winter. Bornstein (1968) estimated that, during one winter, waste heat from fuel burning in New York City was 2-1/2 times the size of solar-driven net radiation. Anthropogenic conversion of energy is one of the major causes of urban-rural temperature differentials. Thus one would expect that if all other factors were equal, the warmer the climate, the weaker the urban heat island intensity. This should also contribute to a latitudinal differentiation in the strength of the island.

The final variable chosen was precipitation. Two factors favoured the choice. Firstly, precipitation is a primary agent in wet deposition processes. Wet deposition is an atmospheric cleansing mechanism associated with either in-cloud scavenging by liquid droplets, ice crystals, or with direct washout during a precipitation event or with all three. Since urban heat islands develop in part because of the higher pollution levels normally found inside the urban air layer (Atwater 1971), areas of high precipitation should have relatively clean air. In addition, most precipitation events are associated with low pressure systems on either a synoptic or local scale. Winds are normally stronger in lows and clouds prevail. These two conditions (wind and cloud cover) are factors which vitiate the development of heat islands (Kingham 1969; Nkemdirim 1980; Sondborg 1950). It seems appropriate, therefore, to use precipitation as a surrogate for all those factors which in combination tend to reduce the strength of heat islands.

The second reason for choosing precipitation as a variable is a pragmatic one. Anticipated changes in precipitation patterns from a 2 x $CO_2$ scenario are available from GCMs. Thus, the projected values of precipitation, along with temperature, can be substituted into regression models derived under current conditions to yield estimates for $CO_2$-modified heat islands.

A literature search provided data on representative heat islands, $\overline{\Delta T_{u-r}}$, for 40 cities from five continents (Table 1). The data covered over 100° of latitude, from Christchurch, New Zealand (43°42'S) to Fairbanks, Alaska (64°49'N). The regional mean annual temperature and

Table 1. List of cities, latitudes, and $\overline{\Delta T_{u-r}}$ used in the current study.

| City | Latitude | $\overline{\Delta T_{u-r}}$ |
|---|---|---|
| Poona, India | (1) 18°32'N | 6.0 (Daniel & Krishnamurthy 1973) |
| Mexico City, Mexico | (2) 19°24' | 4.5 (Jauregui 1970) |
| Houston, USA | (3) 29°46 | 4.5 (Runnels et al. 1972) |
| Dallas, USA | (4) 32°47' | 4.0 (Ludwig 1968) |
| Los Angeles, USA | (5) 34°03' | 3.0 (Landsberg 1972) |
| Hibariga-Oka, Japan | (6) 35°42' | 2.0 (Tamiya 1968) |
| San Francisco, USA | (7) 37°48' | 6.0 (Duckworth & Sandburg 1954) |
| Palo Alto, USA | (8) 37°27' | 2.5 (Duckworth & Sandburg 1954) |
| San Jose, USA | (9) 37°20' | 4.5 (Duckworth & Sandburg 1954) |
| Sendai, Japan | (10) 38°15' | 1.5 (Hosokawa & Shitara 1977) |
| Washington, D.C., USA | (11) 38°54' | 3.5 (Woollum 1968) |
| Cincinnati, USA | (12) 39°06' | 3.9 (Clarke & McElroy 1968) |
| New York City, USA | (13) 40°43' | 4.0 (Bornstein 1968) |
| Chicago, USA | (14) 41°47' | 1.0 (Landsberg 1972) |
| Detroit, USA | (15) 49°20' | 0.8 (Sanderson et al. 1973) |
| Hamilton, Canada | (16) 43°15' | 5.5 (Oke & Hannell 1970) |
| Toronto, Canada | (17) 43°39' | 4.5 (Munn et al. 1969) |
| Minneapolis, USA | (18) 44°53' | 2.0 (Stanford University 1953) |
| Montreal, Canada | (19) 45°31' | 3.7 (Oke & East 1971) |
| Vienna, Austria | (20) 48°13' | 5.5 (Bohm & Gabl 1978) |
| Paris, France | (21) 48°58' | 1.7 (Dettwiller 1969) |
| Vancouver, Canada | (22) 49°11' | 7.0 (Maxwell & Oke 1975) |
| Winnipeg, Canada | (23) 49°54' | 1.0 (Stanford University 1953) |
| Calgary, Canada | (24) 51°03' | 5.1 (Truch 1977) |
| London, England | (25) 51°28' | 6.7 (Chandler 1967) |
| Reading, England | (26) 51°28' | 0.6 (Parry 1967) |
| Lunen, W. Germany | (27) 51°36' | 3.5 (Kuttler & Schreiber 1984) |
| Utrecht, Netherlands | (28) 52°06' | 1.3 (Conrads & van der Hage 1971) |
| Sheffield, England | (29) 52°31' | 7.0 (Garnett & Bach 1967) |
| Berlin, W. Germany | (30) 52°31' | 5.0 (Landsberg 1972) |
| Edmonton, Canada | (31) 53°33' | 6.5 (Hage 1971) |
| Lund, Sweden | (32) 55°42' | 2.0 (Lindqvist 1968) |
| Moscow, USSR | (33) 55°45' | 2.0 (Landsberg 1972) |
| Uppsala, Sweden | (34) 59°02' | 4.5 (Sundborg 1950) |
| Helsinki, Finland | (35) 60°12' | 8.0 (Fogeberg et al. 1973) |
| Fairbanks, USA | (36) 64°49' | 6.0 (Benson & Bowling 1975) |
| Quito, Ecuador | (37) 0°13'S | 5.0 (Hannell 1976) |
| Johannesburg, S. Africa | (38) 26°15' | 5.0 (Goldreich 1984) |
| Adelaide, Australia | (39) 34°56' | 1.0 (Lyons & Cutten 1975) |
| Christchurch, New Zealand | (40) 43°42' | 6.7 (Kingham 1969) |

precipitation, usually obtained from data taken at the nearest international airport, were obtained for each city either from the pertinent reference or from published meteorological summaries. The population size of the city was obtained either from the article or from census data.

## 2.2 ANALYSIS

Estimates of three future conditions were made. The population of each urban centre was projected to the year 2050 based on growth rates published by the United Nations (1985). Projection of temperature and precipitation for each city were obtained by adjusting the present 30-year normal by the average change projected for the grid in which the city is located under the 2 x $CO_2$ scenarios of the GFDL and GISS models.

Urban heat island intensity was initially regressed against each of the logs of population, mean annual temperature, and mean precipitation. Subsequently, it was regressed against all three predictors combined. The latter equation was then used to assess the magnitude of the heat island for each of the 40 cities under the 2 x $CO_2$ scenario. Subsequently, the temperature of each urban area was derived as the sum of the regional temperature projected by the GCMs plus the predicted heat island intensity.

The relationship between gas consumption and temperature in the city of Calgary was obtained as follows. Firstly, the time series of gas consumption was plotted and examined for possible correlation with population growth. Secondly, the series was detrended to eliminate the population factor and, by implication, urban growth. Thirdly, the residual series was regressed against both the mean annual temperature and the annual heating degree days (degree days below $18^{o}C$) and a regression equation derived. These analyses formed the basis for adjusting current consumption values to estimates under 2 x $CO_2$.

## 3. RESULTS

### 3.1 RELATIONSHIP BETWEEN REPRESENTATIVE URBAN HEAT ISLANDS AND THREE CONTROL VARIABLES

The relationship between urban heat island intensities and each of the three predictor variables is quantified in Table 2. The correlation

Table 2. Relationship between representative heat island intensities and three control variables.

| Control Variable | Regression Variable | Correlation Coefficient | Equation Number |
|---|---|---|---|
| Population | $1.42 \log P - 1.993$[a] | 0.68 | 1 |
| Mean Temperatue | 8.097 to 0.262 T | -0.63 | 2 |
| Mean Precipitation | 7.933 to 0.004 R | -0.84 | 3 |

[a] Symbols: P = Population; T = mean annual temperature °C
R = mean annual precipitation (mm)

coefficients and regression equations were statistically tested at $\alpha = 0.01$ and were found to be highly significant. The following conclusions were drawn from the relationship:

1. The intensity of urban heat islands is a direct but non-linear function of city population size.
2. A threshold population of less than 100 is all that is required for the occurrence of a measurable urban heat island.
3. With population growth, larger increases in heat island intensity will be made in smaller cities compared to larger ones. San Jose, for example, would experience an increase in intensity of 0.23°C per 100 000 new inhabitants compared to only 0.04°C per 100,000 for London, England.
4. The relationship between $\overline{\Delta T_{u-r}}$ and the mean regional temperature is negative, which confirms the hypothesis on which the selection of temperature as one of the control variables was based.
5. Equation 2 suggests that the maximum mean annual temperature at which $\overline{\Delta T_{u-r}}$ would vanish is $31.2^{\circ}C \pm 2.3^{\circ}C$.
6. Based on the 2 x $CO_2$ scenario, the mean annual temperature of representative heat islands will decline from the present 5.23°C to 3.89°C if there is no change either in population or precipitation.
7. $\overline{\Delta T_{u-r}}$ is highly sensitive to differences in precipitation *ceteris parabus*. The higher the mean annual precipitation, the weaker the urban heat island.

## 3.2 THE JOINT ANALYSIS

The results of the analyses reported above show that $\overline{\Delta T_{u-r}}$ exhibits degrees of sensitivity to differences in population, temperature, and precipitation. It strengthened with increasing population and weakened with both temperature and precipitation increases. Since all three variables operate jointly under the 2 x $CO_2$ scenario, a multiple regression equation was derived to link their effect. (eq. 4):

$$\overline{\Delta T_{u-r}} = 6.63 + 0.28 \log P - 0.09\overline{T} - 0.003\overline{R} \qquad (4)$$

The multiple correlation coefficient was 0.93. Both the regression constants and the coefficients of multiple regression were highly significant at $\alpha = 0.01$. In addition, all three control variables contributed significantly to the coefficient of determination of $\overline{\Delta T_{u-r}}$ even after accounting for the collinearity among them.

In light of the high statistical significance achieved in the joint analysis, equation 4 was used to derive synthetic $\overline{\Delta T_{u-r}}$ for each of the 40 cities under 2 x $CO_2$ (Table 3). The net effect is a general lowering of heat island intensities. The average reduction was only 6%. This low value is mainly due to the upward pressure exerted on $\overline{\Delta T_{u-r}}$ by projected increases in population. Johannesburg, for example, would probably experience an increase in intensity due mainly to a very large population growth projected for the city. Latitudinal differences in $\overline{\Delta T_{u-r}}$ are also less apparent in the synthetic data than they were in Table 1. The spatial variability in the new data is 33% lower than in the old data. This implies that under a 2 x $CO_2$ climate, larger reductions in urban heat island intensity will occur in the higher latitudes (where climatic change will be more pronounced) than in the lower latitudes.

### 3.3 GAS CONSUMPTION IN CALGARY

Natural gas sold to residential and commercial terminals in Calgary is used for space (85%) and water heating (15%). Because of the potential contribution of both sources to urban warming, no distinction was made between them. There was also no distinction made between residential consumption (R) (Figure 1) and commercial usage (C) (Figure 2) since they are highly correlated ($r = 0.99$) and appear to be driven by the same forces. Consequently, the foregoing analysis is based on the combined series (Figure 3).

Gas sales rose from $1.58 \times 10^6$ GJ in 1916 to $54.95 \times 10^6$ GJ in 1986 and appear to be forced upwards by urban growth. (This growth may be represented by population.) The almost perfect correlation (0.97) between population and gas sales is evident from a comparison of the population time series (Figure 4) and the sales series (Figure 3). The regression equation which describes their relationship is given by:

$$G\ (R + C) = (90P - 3.06 \times 10^6)\ \text{GJ} \tag{5}$$

Table 3. Present and projected heat island intensities.

| City | Latitude | $\overline{\Delta T_{u-r}}$ Present | Projected |
|---|---|---|---|
| Poona, India | 18°32'N | 3.98 | 4.00 |
| Mexico City, Mexico | 19°24' | 5.00 | 4.97 |
| Houston, USA | 29°46' | 3.01 | 2.97 |
| Dallas, USA | 32°47' | 4.04 | 4.02 |
| Los Angeles, USA | 34°03' | 6.90 | 6.90 |
| Hibariga-Oka, Japan | 35°42' | 1.62 | 1.58 |
| San Francisco, USA | 37°48' | 5.47 | 5.50 |
| Palo Alto, USA | 37°27' | 5.08 | 4.94 |
| San Jose, USA | 37°20' | 5.22 | 5.08 |
| Sendai, Japan | 38°15' | 3.47 | 3.43 |
| Washington, D.C., USA | 38°54' | 4.04 | 3.99 |
| Cincinnati, USA | 39°06' | 4.14 | 4.09 |
| New York City, USA | 40°43' | 4.25 | 4.20 |
| Chicago, USA | 41°47' | 7.41 | 7.33 |
| Detroit, USA | 42°20' | 5.21 | 4.99 |
| Hamilton, Canada | 43°15' | 4.95 | 4.66 |
| Toronto, Canada | 43°39' | 5.28 | 5.01 |
| Minneapolis, USA | 44°53' | 5.88 | 5.58 |
| Montreal, Canada | 45°31' | 4.59 | 4.13 |
| Vienna, Austria | 48°13' | 5.51 | 5.01 |
| Paris, France | 48°58' | 5.85 | 5.35 |
| Vancouver, Canada | 49°11' | 4.21 | 3.52 |
| Winnipeg, Canada | 49°54' | 6.43 | 5.98 |
| Calgary, Canada | 51°03' | 6.52 | 6.08 |
| London, England | 51°28' | 5.84 | 5.30 |
| Reading, England | 51°28' | 5.38 | 4.81 |
| Lunen, W. Germany | 51°36' | 4.62 | 3.91 |
| Utrecht, Netherlands | 52°06' | 5.05 | 4.38 |
| Sheffield, England | 52°31' | 5.05 | 4.33 |
| Berlin, W. Germany | 52°31' | 7.57 | 7.27 |
| Edmonton, Canada | 55°33' | 6.54 | 6.05 |
| Lund, Sweden | 55°42' | 5.40 | 4.74 |
| Moscow, USSR | 55°45' | 8.15 | 7.92 |
| Uppsala, Sweden | 59°02' | 5.91 | 5.24 |
| Helsinki, Finland | 60°12' | 5.73 | 4.93 |
| Fairbanks, USA | 64°49' | 7.21 | 6.78 |
| Quito, Ecuador | 0°13'S | 3.68 | 3.83 |
| Johannesburg, S. Africa | 26°15' | 4.87 | 5.08 |
| Adelaide, Australia | 34°56' | 5.25 | 5.30 |
| Christchurch, New Zealand | 43°42' | 5.12 | 4.96 |
| Mean | | 5.23 | 4.96 |

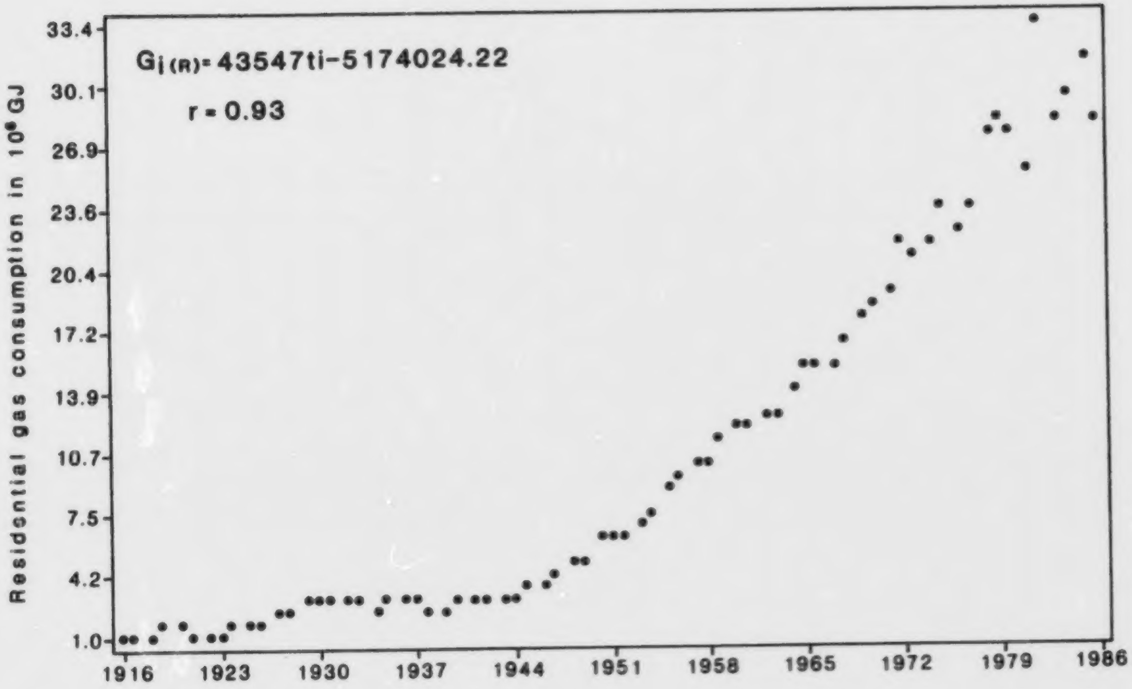

Figure 1. Time series of gas (G) sold to residential terminals (R) in year $t_i$ beginning from 1916 when i = 1. Linearity is assumed for simplicity.

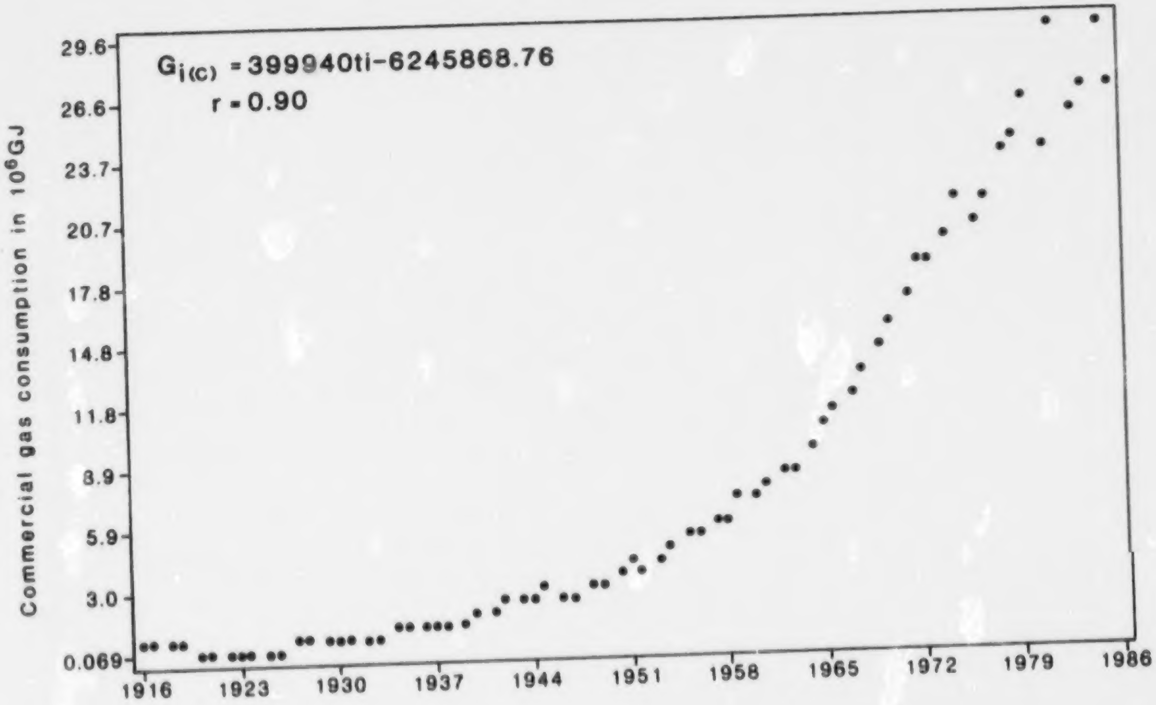

Figure 2. Time series of gas sold to commercial terminals (R) in Calgary.

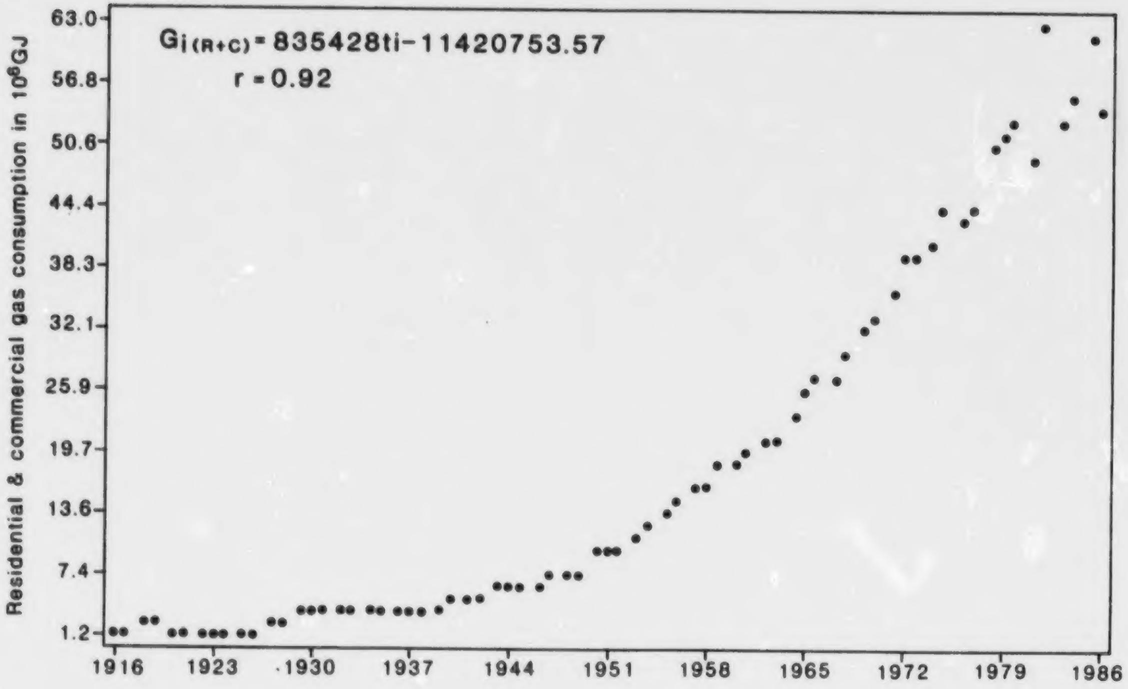

Figure 3. Time series of the combined gas sales to commercial and residential terminals in Calgary.

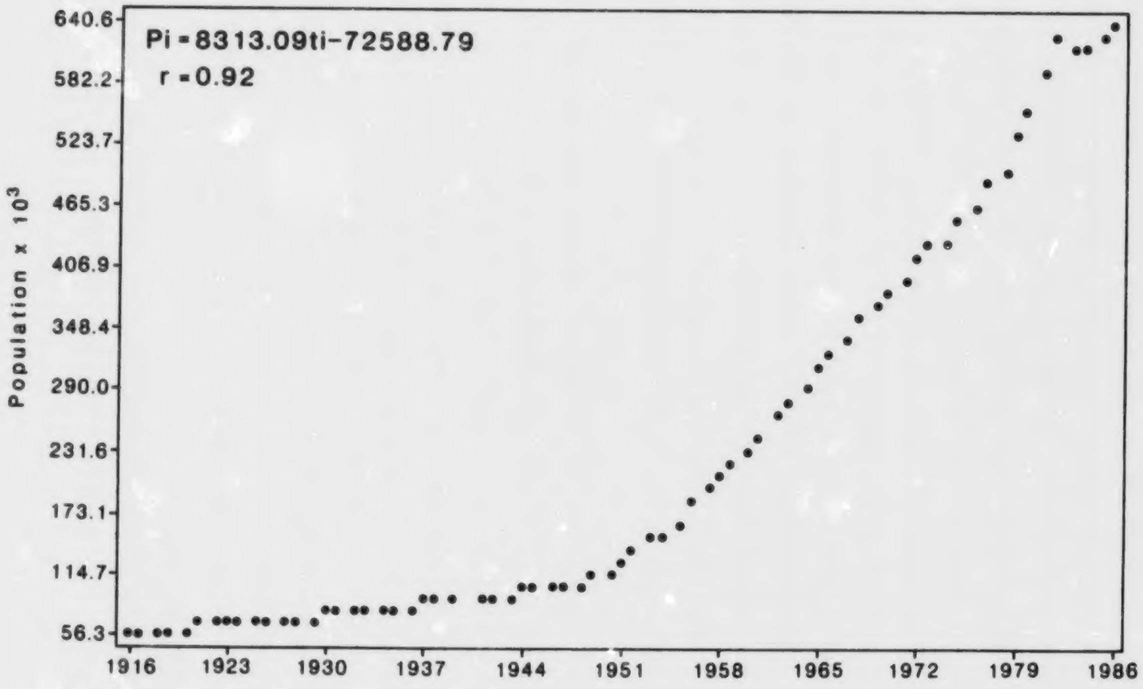

Figure 4. Time series showing the growth of population in Calgary from 1916 to 1986.

where G (R + C) is the gas supply and P, the corresponding population. Both the regression and correlation coefficients are significant at $\alpha = 0.01$.

There are two components to the energy consumption pattern. The first component, the amount required by the population to survive the climate, is fixed. It is determined by the population size and the mean annual city temperature. The second component is dependent on the annual/seasonal temperature variation. Because of the near perfect match between gas consumption and population, the first component was isolated by removing its trend from the consumption series (Figure 5). Detrending is preferred to residuals because it preserves consumption levels as deviations per capita. The second component was obtained by regressing the detrended series against (a) the mean annual temperatures and (b) the annual cumulative heating degree days referenced at 18°C (Figures 6 and 7 respectively). As one would expect, the two correlation coefficients are equal. However, in calculating the city's energy requirement, under tne 2 x $CO_2$ scenario, the latter variable was used.

These analyses reveal that the "fixed" factor accounts for 84% of Calgary's gas consumption, 12% is due to temperature variability and the remaining 4% constitutes the "error" term. Under the 2 x $CO_2$ scenario, and based on the earlier calculation of the change in heat island intensity, climatic change in Calgary should result in an increase in the mean annual temperature of between 3.8°C and 4.2°C . By allocating future gas consumption according to the components identified above, and using the mean per capita gas sale of the previous 70 years as the base, it is estimated that, under a 2 x $CO_2$ climate, gas sales will drop between 24 and 33% per capita below the current average.

The projected lowering in demand does not reflect the full impact of climatic change on energy use. There might be a rise in energy demand for cooling in the summer. Reliable figures for a projection of energy load for cooling are unavailable. However, a rough calculation, based on U.S. data, suggests a 5 to 10% increase in the demand for cooling-related energy.

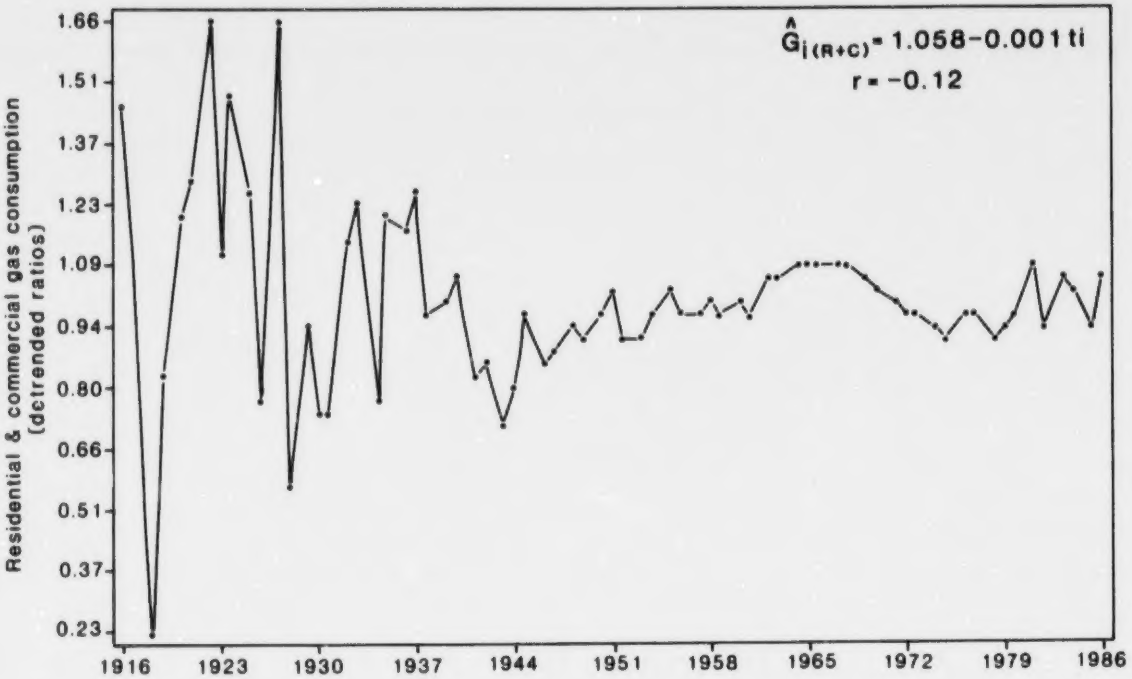

Figure 5. Detrended series of gas ($G_1$) sold to residential and commercial terminals in Calgary.

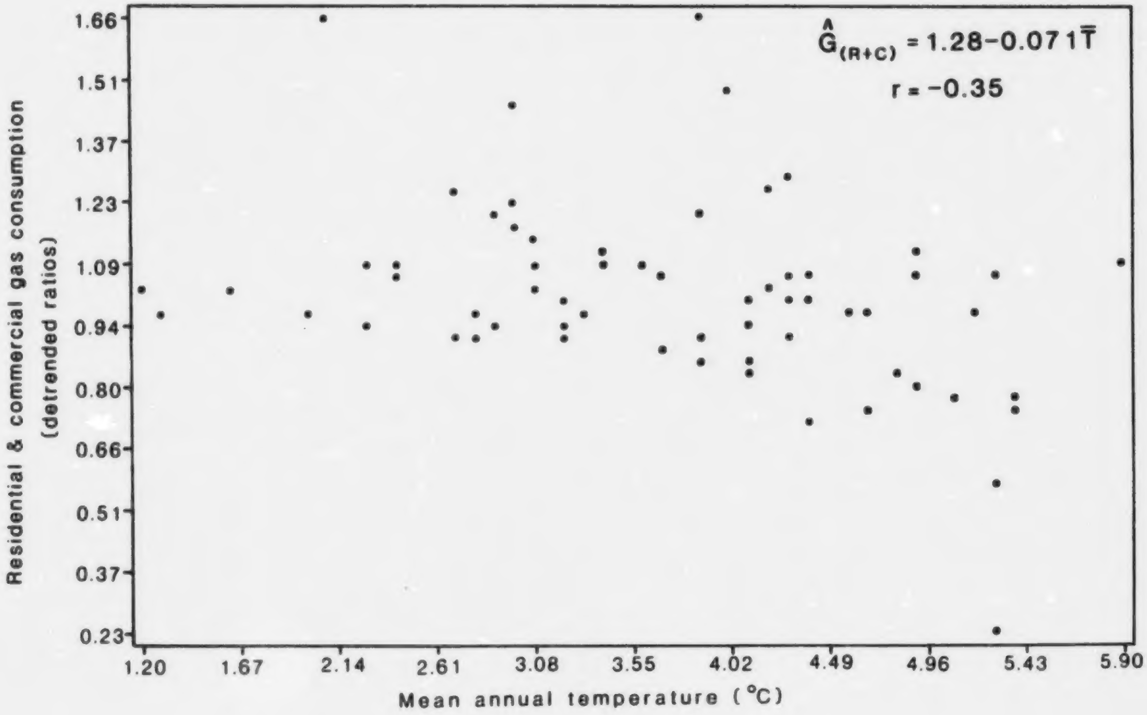

Figure 6. Relationship between mean annual temperature (T) and the detrended gas series in Calgary.

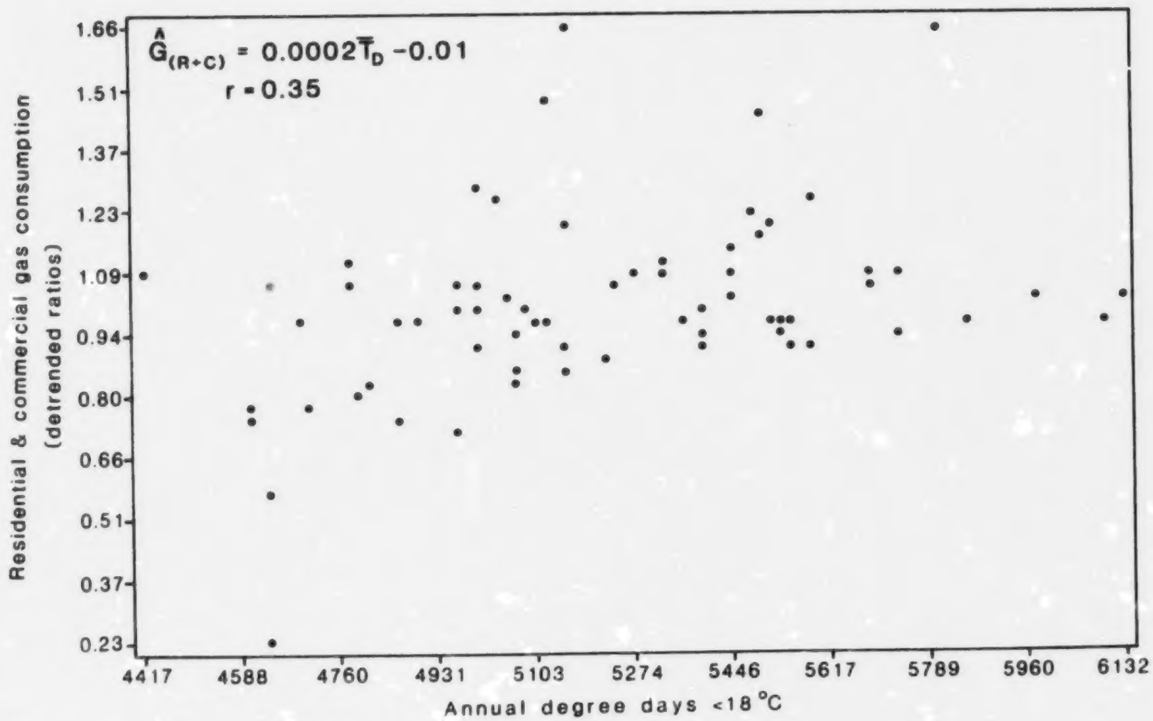

Figure 7. Relationship between annual heating degree days below $18^oC$ ($T_D$) and the detrended gas series for Calgary.

## 4. CONCLUSION

The impact of $CO_2$-induced climatic change on urban temperatures cannot be assessed without an initial recognition of its potential effect on urban heat islands. It appears, however, that under a 2 x $CO_2$ scenario, the change in the intensity of heat islands will be relatively small. Although the higher temperatures and precipitation projected under the scenario may exert a downward pressure on the island's intensity, population growth could compensate for some of the loss in strength through an upward push on the island's intensity. On the whole, depending on latitude, heat island intensity should decline by 6 to 20% of their current value. For Calgary, the projected decrease is about 7%. Because of the small values involved, it is felt that urban areas will experience temperature increases equivalent to those projected for the region to which they belong. Calgary's mean annual temperature, under the 2 x $CO_2$ scenario, should be between 3.8 and 4.2°C higher than at present. This is estimated to reduce the demand for energy and space heating by between 24 and 33% per capita. However, the demand for energy for cooling during the summer could rise by between 5 and 8% over its current low levels.

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# IMPACT OF CLIMATIC CHANGE AND VARIABILITY ON RECREATION IN THE PRAIRIE PROVINCES

by

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## ABSTRACT

Recreation managers are involved in planning, designing, and operating recreational facilities. Many outdoor recreation activities depend on the physical resource base directly provided by the climate (e.g., snow, water) or depend on other resources indirectly produced by the climate (e.g., vegetation, waterfowl). Recreation managers attempt to reduce the effects of climatic variability by increasing the consistency in the quality and quantity of recreation opportunities through artificial means (e.g., snow making, irrigation). This establishes a reputation for consistency in experience, which attracts clients.

Long-term changes in precipitation, temperature, and winds will result in major shifts in recreation patterns (e.g., hunting) and increase the costs of artificial management techniques (e.g., irrigation). Activities of the winter season have the greatest reliance on climate resources. Areas with marginal suitability, because of extreme variability or a consistent lack of the required climate resources, will suffer the most.

Activities requiring major capital and operating costs will be affected the most. Recreationists will respond by decreasing participation frequency and/or shift to other areas with more suitable conditions.

A review of the nordic snow management program in Kananaskis Country is used as an example of an intensive approach to snow management that has evolved to cope with climatic variability, high public use, and changes in the requirements of the recreation activity.

## 1. INTRODUCTION

Outdoor recreation encompasses a wide range of activities. A few major outdoor activities are, directly and/or indirectly, extremely reliant on climate. Recreation activities on the prairies are seasonal and can be classified from differences in temperature and snow. Masterton et al. (1976) defined these seasons as: (1) winter season (the period between the first and last dates of snow cover of 2.5 cm); and (2) summer season (the period starting two weeks after the last date of snow cover). The latter includes spring and fall shoulders around the period of high summer (the period with mean daily maximum temperatures above 16°C).

Masterton et al. (1976) observed that the boundary of the aspen groveland/boreal forest and the 170-to-180 day winter season are approximately the same. The bulk of the prairie population, therefore, experiences a 160 to 170 day winter (early November to mid-April). They also calculated the period of reliable snow cover; that is, the first and last dates that 2.5 cm of snow remains on the ground for at least seven consecutive days. By this definition, the winter period with reliable snow cover in the southern prairies is about 100 days.

Masterton et al. (1976) recognized three basic categories of recreation pursuits: (1) dry-terrain (e.g., golf, picnicing, walking, camping); (2) water-based (e.g., sunbathing, swimming, boating, fishing); and (3) snow- and/or ice-based (e.g., nordic skiing, alpine skiing, snowshoeing, snowmobiling, tobogganing, ice fishing, skating). Recreation activities with similar climate requirements can be grouped within each category. Masterton et al. (1976) list climate requirements for some activity groupings. Biophysical requirements, including climate, for a wide range of activities can be found in More and Fleming (1982). These requirements refer to natural conditions. Requirements may change with technological advances in clothing and equipment and with the evolution of individual recreation activities.

These publications do not address the topic of climate requirements for intensive facility management or the enhancement of the natural resource base. An example of such requirements for nordic ski management is presented in this paper to illustrate the approach taken by recreation managers to overcome climate variation (temperature, snowfall, and snow retention). The example also illustrates the high cost of intensively managing recreation facilities.

The impact of climatic change on recreation can be viewed in terms of changes in climate parameters and resultant changes in other biophysical resources. The assumptions followed in this paper are: (1) precipitation will be reduced in the southern part of the prairie provinces, in summer and winter, resulting in a decrease in mean annual precipitation; (2) temperatures will increase and be reflected in a longer summer season (Environment Canada 1986); and (3) the present range of variability and winter synoptic patterns (alternating cold Arctic highs) will continue.

Climatic change will affect the natural resource base with reduced snowpacks and decreased water levels in lakes, rivers, and reservoirs (Environment Canada 1986). Vegetation zones will change with an expansion of grassland and aspen parkland forests (Bruce and Hengeveld 1985; Singh and Powell 1986). These changes in habitats, along with a decrease in winter severity, will result in changes in the distribution and numbers of major big game, waterfowl, and upland game bird species.

## 2. DECREASES IN RECREATION OPPORTUNITIES WITH CLIMATIC CHANGE

### 2.1 LAKES, RESERVOIRS, AND RIVERS

Water in surface waterbodies is critical for the production of fish and for boating/swimming opportunities. Many surface waterbodies in the prairies are shallow and tend to be eutrophic. Decreased depth and increased air temperatures will result in warmer water. Both algae and aquatic (submergent and emergent) plant growth will increase. This will decrease the quality of swimming and boating opportunities (Table 1) and, in shallow waterbodies, may lead to oxygen deficiency for fish.

The surface area of waterbodies is important for motorboating and sailing (Table 1). Waterbodies should be greater than 80 ha in size, as high-powered boats require 8 ha per boat and large sailing craft require 15 ha per boat. A minimum depth of 1.5 to 2.5 m is required. Increased reservoir drawdown for irrigation during the peak boating season in mid- to late-summer will severely curtail boating.

Table 1. Minimum climate related requirements for summer recreation activities.

| | Water Based Activities | | | | |
|---|---|---|---|---|---|
| | MOTOR BOATING | WATER SKIING | SAILING | FISHING | SWIMMING/ SUNBATHING |
| Air Temperature (°C) | 15 to 35 | 16 to 35 | 10 to 35 | 15 to 30 | 15 to 30 |
| Wind (km/h) | < 50 | < 15 | 15 to 50 | < 15 | < 15 |
| Water Temperature (°C) | 2 to 20 | 10 to 20 | 10 to 18 | < 18 | 15 to 20 |
| Precipitation | Nil | Nil | Nil | Nil | Nil |
| Lake Size, min (ha) | > 80 | > 100 | > 30 to > 100 | 20 to 80 | 20 to 40 |
| opt (ha) | 400 | 800 | 800 | 400 | 800 |
| Lake Depth (m) | 1.5 to 2.5 | > 2.0 | 1.5 to 2.0 | 0.5 to 1.0 | 0.5 to 2.0 |
| Carrying Capacity | 1 ha/boat | 5 ha/boat | 10 ha/boat | -- | -- |
| Aquatic Vegetation | Minor emergent | Minor submergent | Minor submergent | Minor emergent | Nil |

| | Summer Dry Terrain Activities | | |
|---|---|---|---|
| | CAMPING | PICNICING | GOLF |
| Air Temperature (°C) | > 10 | 10 to 25 | 10 to 30 |
| Wind (km/h) | < 40 | < 20 | < 20 |
| Precipitation | Nil to light | Nil | Nil |

Source: More and Fleming (1982).

Increased air and water temperatures will reduce the onset of surface freezing and cause earlier spring melting. Lakes normally freeze in mid- to late-November. Surfaces must freeze to at least 15 cm to support an adult person. Thicker ice is needed to support vehicles or large numbers of people. A late freeze and earlier melt will reduce the time period for ice fishing, lake snowmobiling, and skating opportunities (Table 1).

River flow for whitewater kayaking/canoeing is best during the spring and early summer peak run-off. Decreased run-off and shorter run-off periods will curtail these activities. Family canoeing will mainly be possible only on major watercourses.

## 2.2 HUNTING

Wildlife is directly dependent on vegetation for food and shelter. Progressive changes in vegetation zones will result in a decrease in boreal species in the southern part of the western provinces and a corresponding increase of species adapted to prairie and aspen parkland zones. In addition, the progressive drying of prairie potholes will decrease waterfowl production. A reduction in climate severity will increase winter survival of those species not well adapted to cold and snow (Olson 1984).

These scenarios indicate a reduction in hunting opportunities for both waterfowl and boreal species such as moose. Hunters will shift their activity patterns to the north or will adapt to different species. Any overall reduction will decrease tourism opportunities for out-of-province hunters.

## 2.3 NORDIC SKIING/SNOWMOBILING

Nordic skiing and snowmobiling are dependent on adequate snowfall, retention of snowpack, and moderate temperatures. Temperatures below -20°C make skiing difficult and unpleasant. Extremely cold temperatures make both of these activities dangerous. Excessively warm temperatures can evaporate the snowpack or change its consistency to slush, which turns to ice when refrozen; skiing becomes difficult and unpleasant. Low snowfalls and warm temperatures combine to make an undependable situation. Areas subjected to chinooks may have a short and inconsistent skiing or snowmobiling season (Table 2).

Table 2. Climatic requirements for winter recreation activities.

| ENVIRONMENTAL CONDITION | NORDIC SKIING | ALPINE SKIING | SNOW SHOEING | SNOW MOBILING |
|---|---|---|---|---|
| Snow Season | Nov. to Apr. | Nov. to May | Nov. to Apr. | Nov. to Apr. |
| Snow Depth (cm) | 20 to 30 min.<br>60 opt | 20 to 30 min.<br>60 opt | 20 to 30 min.<br>60 opt | 30 min.<br>60 opt. |
| Snow Density ($g/cm^3$) | < 0.6 | < 0.6 | 0.2 to 0.6 | 0.4 to 0.10 |
| Air Temperature (°C) | -2 to -15 | 5 to -20 | 10 to -40 | 10 to -30 |
| Snow making (°C) | -6 to -15 | -6 to -15 | N/A | N/A |
| Wind (km/h) | < 20 | < 15 | < 45 | <45 |
| Wind Chill ($watts/m^2$) | 700 | 700 | 1600 | 1400 |

Source: More and Fleming (1982).

Competitive events at ski areas which rely on natural snow accumulation will be hard to schedule with certainty. In order to provide suitable conditions for competition, area managers will have to intensively manage trail systems and make or move snow to maintain heavily used or exposed trail sections.

### 2.4 ALPINE SKIING

Alpine skiing in the prairies is confined to deep glacial river valleys (where aspect and cold air drainage help retain snow) or to the foothills and front ranges in Alberta. Many ski areas have, and require, the facilities for making artificial snow. These facilities are used to prepare a base in advance of natural snow accumulation, to maintain heavily skiied portions of runs, and to recover from warm periods and droughts.

Night-time and day-time temperatures are critical for snow making and retention. Temperatures between -6°C and -16°C are preferred for snow-making because of the quality and quantity of snow that can be produced. Decreased precipitation will result in increased reliance on snow-making. However, an increase in average daily temperatures above -6°C would make snow-making difficult, reduce the snow-making season (see Masterton et al. 1976 for dates for selected cities), and reduce retention of the produced snow (Table 2).

Ski areas depend on Christmas season revenues to sustain their large annual operating costs. Longer autumn shoulders would make it difficult to prepare ski areas if temperatures are warm and if fall snow storms do not occur.

## 3. INCREASED RECREATION OPPORTUNITIES WITH CLIMATE CHANGE

### 3.1 DRY TERRAIN ACTIVITIES

Most dry terrain recreation opportunities will profit from longer high summers and extended summer shoulders (Table 1). Golf, walking, picnicing, and camping will increase with dry, warm summers. Golf courses, prairie campgrounds, and picnic grounds, may require irrigation or increased irrigation as a result of lower precipitation and increased evapotranspiration.

## 3.2 WATER BASED ACTIVITIES

Many water based activities (sunbathing, fishing, boating, and waterskiing) require similar weather to dry terrain activities (Table 1). However, there will be a trade-off between an increased opportunity to participate because of warm, dry weather patterns and a decrease in the physical resource base on which to do the activity. This will be particularly effective for activities requiring large water surface resource bases.

## 3.3 HUNTING

Wildlife species requiring warmer winters and little snow will experience greater winter survival. Upland game birds (e.g., ring necked pheasants) and prairie ungulates (e.g., mule deer, pronghorn antelope) will increase in numbers and distribution. Associated hunting opportunities will increase.

## 4. CASE EXAMPLE: NORDIC SKI MANAGEMENT IN KANANASKIS COUNTRY

Alberta Recreation and Parks manages six nordic ski areas in Kananaskis Country (Figure 1). They include areas for competitive racing, family skiing, citizen races, and ski touring. Some of the areas were planned and developed in the mid-1970s when trails designed exclusively for nordic skiing were unique. These trail systems and their management have evolved considerably as a result of public use levels, special requirements for racers, new maintenance equipment, and very poor winter conditions since the late 1970s.

The optimum climate pattern for ski trail management (Table 3) is the progressive accumulation of snow starting in early November. This allows the public to ski and assist in the natural settling of the snowpack. Early-season snowmobile trail compaction and track setting help to change and firm the base material for the trail tread. A well-developed base is less subject to disturbance by ski traffic and the effects of mild air temperatures. Since the major ski traffic period occurs over the Christmas holidays, a well-prepared base is highly beneficial.

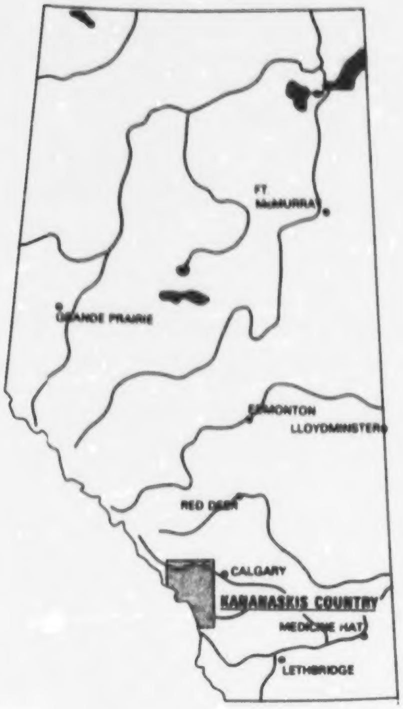
FT McMURRAY
GRANDE PRAIRIE
EDMONTON
LLOYDMINSTER
RED DEER
CALGARY
KANANASKIS COUNTRY
MEDICINE HAT
LETHBRIDGE

Figure 1. Location of Kananaskis Country.

Table 3. Climatic requirements for a nordic ski area snow management program.

| | |
|---|---|
| Snow Season | - mid-November to mid-April |
| Snow Depth | - minimum 8 cm fresh snow for skier on smooth, seeded trail<br>- minimum 10 to 15 cm packed snow for track setting with snowmobile (equal to 20 cm fresh snow) on smooth trail<br>- Increase depth by height of obstacles for non-smooth trails<br>- 30 cm base preferred |
| Storm Frequency | - weekly |
| Storm Intensity | - less than 30 cm per storm |
| Temperature Range | - -2°C to -15°C |
| Wind | - less than 14 km/hr |
| Chinooks | - none or temperature remains below -2°C |

Source: More and Fleming (1982).

Snowfall patterns are storm dependent. Early storms in mid-November, particularly those snowfalls with a high water equivalent, have helped in trail maintenance in the past few years. Without these storms, the subsequent December/January droughts would have produced extremely poor bases for the remainder of the winter. However, late-winter warming trends have created severe problems in meeting scheduled national and international ski competitions. Major efforts have been made to rebuild track treads by ferrying snow with trucks and helicopters.

The last major problem in the Kananaskis area concerns the direct effects of chinooks or their associated warming trends. Major snow melts may prematurely end the ski season if the tracks melt and refreeze to ice. Short-term closures of ski trails, until a fresh snowfall, is the only inexpensive measure to combat this problem.

Problems associated with climatic variability have been partially offset by summer trail maintenance and winter grooming methods. Early snowfalls are allowed to settle naturally. Once depths have reached 10 to 15 cm, the trails are compacted with snowmobiles. This, along with public use, helps to compact and harden the snow and prepare a trail base. About 10 to 15 cm of compacted snow is required before track setting starts. These depths are for trails that have been constructed with smooth tread surfaces and been seeded to low-growing grasses. Trails with rough surfaces (e.g., stumps or rocks) require greater snow depths.

Snow cats, similar to equipment used on alpine runs, are used to move snow with a blade and to renovate and set the track by compacting it with piston-driven attachments. During extreme snowfalls (>30 cm), the snow cats operate continuously to pack the snow. If the snow gets too deep, it must be allowed to settle naturally, or be compacted with snowmobiles, before the snow cat equipment can be used effectively. Decisions on which operation to perform are based on track depths (measured every km), trail surface temperatures, and humidity measurements. Certain grooming equipment and track setters are restricted by surface stickiness and depth of fresh snow.

The seasonal sequence of trail maintenance and snow management is: (1) summer - level trails, remove rocks and debris, and seed to grass; (2) early winter - pack with snowmobile or public skiing, groom with snow cat to level, flatten, widen, and pull in snow from sides to centre; (3) mid-winter - groom, move snow, haul snow, and set track; and (4) late winter/spring - groom with cultivator/powder maker, renovate with firn renovator, and track set with tiller/track setter. Without the intensive management using snow cat grooming equipment, the quality of family and competitive skiing would not be at the level it is today.

## 5. DISCUSSION

The winter and summer drought conditions and temperature variability of the last five years amply demonstrate the reliance of many recreation pursuits on specific climate conditions. The hardest hit activities have been snow and water based.

Recreationists have a degree of flexibility in their response to these impacts. They can travel, within personal economic constraints, to locations where climate conditions for their activity are still favourable. They can reduce their participation to periods when conditions are favourable at their established areas. They can cease to participate at all in their usual activity and undertake new activities or increase their involvement in other activities.

People do change their involvement and level of participation. Surveys in Alberta demonstrate that a wide range of factors such as aging, economic conditions, and work obligations cause people to modify their recreation patterns (Dunn 1986). Unfortunately, factors such as climate suitability have not been specifically assessed.

Regional differences in participation frequency are likely to be directly related to opportunities. Calgarians participate more in alpine skiing than the general population of Alberta. Edmontonians must stay overnight to ski in the mountains whereas Calgarians can ski and return home daily (Manecon Partnership 1986). If precipitation patterns change so that local ski areas no longer have suitable snow conditions, then Calgarians will likely adopt the strategy of Edmontonians. They will travel farther but change to a pattern of skiing for two or more days in succession and remain overnight near the ski resort.

Similarly, recreationists who find that their equipment, such as motorboats, becomes less frequently used because local reservoirs or lakes are too low will eventually find waterbodies that are suitable, travel farther for extended time periods, or drop their activity and sell their equipment.

Where possible, recreation managers are already responding to climatic variability. Few alpine ski resorts in Alberta do not make snow on all or parts of their ski areas to overcome the limitations caused by variable snowfall, to compensate for melting of low elevation snowpacks during warming trends, and to extend the early winter season.

Most ski areas in Alberta try to establish a market demand by opening by November 15 and skiing as late into April as possible. By contrast, ski areas in more southern regions, like Colorado, which typically have far greater snowfalls during a shorter winter than the Canadian prairies, do not attempt to ski until the American Thanksgiving Holiday and close by the Easter Holiday.

An intensive snow management trend is starting to occur at nordic ski resorts. The Kananaskis case study demonstrates the snow management strategy that has evolved to handle variable and insufficient snowfall in a nordic ski area relying on natural snowfall. The Canmore Nordic Centre will be one of few nordic areas using snow-making equipment to meet the requirements for competitive ski training and event scheduling.

This raises the point of economic and social impacts of climatic change on recreationists. Certain recreational pursuits cost recreation managers little in capital development or operating expenses. The enhancement or detraction of these pursuits by climatic change will be only a small economic impact. Recreationists may shift their patterns of participation and may regret the change, but little overall social impact is expected.

Studies in Alberta demonstrate the economic aspects of outdoor recreation. In 1983, average annual total expenditures by outdoor recreationists were in the range of $800 to $1000 (Table 4). This expenditure is composed of costs for travel, equipment, accommodation/meals, and fees/memberships. Activities with the highest expenditures are among the most costly in terms of capital development and operations, and in service

Table 4. Total annual expenditures and participation rates of Albertans for selected outdoor recreation activities in 1984.

| Activity | Total Annual Expenditures | Rates Per Thousand |
|---|---|---|
| Camping | $1022 | 458 |
| Snowmobiling, Boating | 917 | 148/283 |
| Touring | 917 | 573 |
| Alpine Skiing | 885 | 208 |
| Fishing, Hunting | 766 | 349/107 |
| Golf | 599 | 170 |
| Canoeing | 502 | 132 |
| Nordic Skiing | 502 | 129 |

Source: More and Fleming (1982).

costs to recreationists. Despite their high cost, these activities showed a high level of participation (Table 4). The high participation rates in these activities indicate that recreationists invest substantial time and money in order to conduct their preferred outdoor pursuit (Table 4).

Recreational pursuits involving facilities that are costly to construct and to maintain will experience the greatest economic repercussions if the climate changes in ways that are not conducive to these activities. The winter activity most representative of this situation is alpine skiing. Its infrastructure (lift, lodges, runs) costs millions of dollars. Operating costs are several million dollars annually for a large resort. Snow-making may cost between $500 to $1000 an hour. The latter costs are ones that managers prefer to avoid; they must be recovered from revenues to be acceptable expenses. Recreationists will pay for satisfying experiences. However, high charges for unsatisfying conditions will not induce consumers to repeat their visits to a resort.

Masterton et al. (1976) prepared a variety of analyses to assist managers in determining the viability of a region for recreation activities. Using climatic requirements, they determined the mean percentage frequency of suitable days for selected activities, and the number of days suitable for skiing and snowmobiling during the winter. However, the snow depth requirement (2.5 cm) is only 5 to 10% of the actual minimum amount needed for winter activities (nordic skiing, snowmobiling, alpine skiing) (Table 2). Because of this, the suitability calculations for these winter activities are likely over-estimated, particularly for the early season/late season periods. Climatic changes resulting in less precipitation and increased temperatures will further reduce the number of suitable days.

Masterton et al. (1976) also calculated the periods suitable for snow-making. Many locations in the prairies can commence snow-making by early to mid-November. An increase in mean temperature would delay this date. The combination of a reduction in reliable natural snow accumulation and a later date for snow-making raises the likelihood of a shorter season for snow based winter activities on the prairies.

## 6. CONCLUSION

Landscapes are likely to gradually change over the next few decades if climate conditions change as predicted. Recreation managers are largely dependent on landscapes and associated biophysical features to attract and encourage use by recreationists. Increasingly, managers are assisting nature by enhancing the natural resource base to provide consistency in the recreation experience or to provide opportunities that depend on man-made features.

Recreation managers are also dependent on reasonably close access (distance or time from the users, road quality, and landscape attractions on the way). Facilities are placed within reasonable access distances which may not necessarily be in the best natural area. For this reason, managers are becoming more reliant on artificial means to improve these areas. The bulk of the population in the prairies lives in the zone of low precipitation and variable temperatures. Some areas (e.g., southern Alberta) are highly affected by chinook wind patterns.

Because of this, recreational activities requiring a deep, consistent snow base will be affected most severely. Secondly, activities requiring adequate water surface area in the summer will suffer considerably, particularly those competing with the agricultural community for the same water supply. Activities requiring wildlife adapted to wetlands and boreal forests will also suffer.

Certain activities will undoubtedly benefit. These are typically summer-type activities requiring dry, warm weather. From a tourism perspective, this may not be a major consolation. Tourism participation is artificially defined by school holiday periods, weekends, and statutory holidays. The increased summer season may not be of real benefit. In addition, the cost of maintaining vegetation may further reduce the benefits.

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# A COMPARATIVE STUDY OF TORNADOES AND OTHER DESTRUCTIVE WINDSTORMS IN ALBERTA AND SASKATCHEWAN

by

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## ABSTRACT

Preliminary findings are presented from a study of over 700 tornadoes and over 1000 other destructive windstorms in Alberta and Saskatchewan in the years from 1910 to 1960. These storms were responsible for 116 deaths, 463 persons injured, and the destruction of 1550 substantial buildings, 2040 large barns and rinks, and 5400 other buildings. Of all types of windstorms, tornadoes caused the most deaths and injuries and the most severe building damage. Total per-storm injuries and building losses were significantly larger in Saskatchewan than in Alberta for both tornadoes and other storms. However, the number of fatalities from non-tornado winds were similar in the two provinces.

Most tornadoes in Alberta and Saskatchewan, as in other regions of the world, were small and short lived. An evaluation of tornado occurrences in the largest urban areas clearly showed the futility of attempts to determine complete tornado frequencies for the region as a whole. The problem results from relatively large numbers of weak tornadoes that touch down unobserved or unreported in rural ares. In analyzing tornado frequencies, attention was focussed on the most intense events for which the statistics are thought to be most reliable. Although tornadoes have been reported as early as February and as late as November, 90 percent occur between June 1 and August 15. Variation in numbers of tornadoes with the seasons were similar in both provinces. The frequencies of weak tornadoes has increased markedly in recent years; this is attributed to improved observation and reporting. The frequencies of both intense tornadoes and other destructive windstorms evidently decreased from about 1915, or earlier, to about 1940. After 1940, the frequencies of such storms showed no marked trends, but were characterized by large year-to-year variations.

Within settled areas of the provinces, the frequencies of the most intense tornadoes in areas of 10 000 square kilometers varied by a factor of 10 from one region to another. The highest frequencies were found in southeastern and south-central Saskatchewan and, to a lesser extent, in a band through central Alberta from near Edmonton to west of Medicine Hat.

# ACKNOWLEDGMENTS

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## 1. INTRODUCTION

This report on the climatology of tornadoes and other destructive windstorms in Alberta and Saskatchewan was prepared for submission to this Symposium at the request of Dr. H.S. Sandhu, Chairperson of the Alberta Climate Advisory Committee. The contents of the report were first presented to the Alberta Centre of the Canadian Meteorological and Oceanographic Society in Edmonton on 1984 December 13, but were not published at that time because the collection of storm data was incomplete. Data collection is still incomplete at this time, and, therefore, it is emphasized that the results described here are tentative and subject to possible revision following analyses of a more complete data set. For example, recent results suggest that the number of fatalities due to drowning following sudden windstorms on prairie lakes exceed those due to all other windstorm causes combined.

A study of past occurrences of destructive winds, including tornadoes, in Alberta and Saskatchewan was initiated by the author in 1975. Previous work by McKay and Lowe (1960) had shown that tornadoes in particular were responsible for serious loss of life and property in western Canada. Because of recent rapid growth in the population and areal extent of many cities in the west and because of an increasing number of large structures such as high-rise apartment buildings, gas plants, refineries, and other commercial and industrial buildings, it seemed desirable to acquire a more extensive data set as a basis for assessment of wind hazard to people and structures in the region.

The Preface to the report by Lowe and McKay (1962) on tornadoes in western Canada is as valid today as it was 25 years ago and deserves to be repeated.

> "Most Canadians think of the tornado as a United States phenomenon - a storm whose ravages are confined south of the 49th parallel. Thus when a tornado demolished the heart of Regina in 1912, Lieutenant Governor Brown explained:
>
> 'A cyclone had come further north than ever before . . . had got out of its natural path and area . . .'

> Popular opinion in our day is not too dissimilar, for recently a leading prairie newspaper published a picture of an unusual cloud which had been seen near Morden. The cloud was described as resembling a waterspout; there was no recognition of the fact that it was a funnel cloud associated with a tornado.
>
> However, tornadoes do indeed occur on the Canadian prairies, and much more frequently than is commonly supposed. Due to rather sparse settlement on our plains they frequently pass unnoticed, leaving as their mark only a shattered barn on some outlying farm, or a swath of uprooted, twisted trees cut through woodland. It is only when one of these vicious storms strikes through a town or village, such as Kamsack, Saskatchewan in 1977, or Vita, Manitoba in 1955, that Canadians are shocked to realize they are not immune."

A second reason for the present study was the discovery by McKay and Lowe (1960) of significant differences in the tornado statistics between the United States and Canada. They found that weather conditions favourable for tornadoes in the midwestern States were not often duplicated in western Canada. In particular, it appeared that in Canada the low-level moisture needed for severe thunderstorms was often supplied locally by transpiration from crops and forests rather than by transport from the Gulf of Mexico or other seas. Central Alberta is known worldwide as a major hailstorm region. Is it possible that tornadoes, which are much smaller than hailstorms, are also relatively frequent there but have escaped notice because of low population density?

For identification of severe storms, McKay and Lowe (1960) relied on the Free Press Weekly in Winnipeg, Manitoba and responses to requests from subscribers to 75 daily and weekly newspapers in the three prairie provinces. By 1975, more sources of data were available on microfilm and in books, thus opening the door to a comprehensive study of past storms. A survey of these data sources is near completion and it is possible to describe some of the findings. Newark (1984), in his report on Canadian tornadoes, used this study to provide a preliminary list of tornadoes in Alberta for the period 1950 to 1979.

## 2. DATA SOURCES

For the purposes of this study, it would be ideal to have a dense, regularly-spaced network of trained observers equipped with weather instruments, cameras, and upper-air observing systems in operation throughout the year over a long period of time. In practice, we have a sparse network of surface weather stations irregularly spaced at an average interval of 150 km or more. Upper air measurements are available only at 12-hour intervals at Edmonton from the late 1940s. Radar data are available only for the most recent years. It is not surprising then that tornadoes and other severe local winds were rarely observed at weather stations.

The only available alternative large data sources are daily and weekly newspapers and family recollections that have been published in community history books. The present study is based on these sources and on storm reports collected by the Atmospheric Environment Service, the Alberta and Saskatchewan Hail Studies Projects, and responses by the public to requests for specific information. Storms which caused no damage to life or property, because of their location and path, remain largely unreported.

Several hundred community history books are available for each province. In this study, about 300 history books from the settled regions in Alberta and Saskatchewan were used. Each book describes events on a farm-by-farm basis over an average area of about 6 townships or 500 $km^2$ (Hage 1977). These descriptions have proven to be excellent sources of detailed information on storm locations and damage. In addition, all major daily newspapers, and many of the weekly newspapers, were scanned for data. All written reports were photocopied and filed by year and province.

## 3. WINDSTORM TYPES

In order to prepare quantitative comparisons, the storms were subdivided into tornadoes and "other destructive windstorms". The types of "other destructive windstorms" known to have caused significant damage in either, or both, provinces are:

1. Cold front;
2. Intense pressure-gradient associated with a synoptic-scale low pressure centre;
3. Chinook;
4. Valley wind resulting from a strong pressure gradient;
5. Downdraft, gust front, or downburst (Fujita 1985) associated with a thunderstorm or convective complex; and
6. Fire devil.

Combinations of these windstorm types are common. For example, a cold front may be accompanied by tornadoes and severe thunderstorm winds; it may be followed within a few hours or a day by strong, pressure-gradient winds. Although dust devils are very common in Alberta and Saskatchewan, especially in April and May, there is no compelling evidence of structural damage even from those that are several metres in diameter and that extend many kilometers up into the atmosphere. Intense cold fronts occasionally are accompanied by destructive wind gusts of short duration, usually from the northwest quadrant. The frontal wind gusts are followed by a lull and then, at times, by one or more periods of strong winds of much longer duration caused by pressure gradients associated with the low pressure centre (Hage 1954). Structures weakened by the frontal gusts may be demolished by subsequent pressure gradient winds. An outstanding example was the cold front of 1930 November 22, which demolished a basilica, several houses, and many other buildings as it crossed central Alberta.

Strong chinook winds are commonplace in southwestern Alberta and, to a lesser extent, in the foothills of the Peace River region. In these regions, special precautions are taken to minimize structural damage. Nevertheless, on rare occasions such as 1970 February 17-18, and 1962 November 19, railroad boxcars were overturned, school roofs torn off, and many buildings destroyed.

The only known destructive valley winds in Alberta occur in the Coal Branch region of the McLeod River valley southwest of Edson. On rare occasions, severe building damage has occurred there from strong south winds which accompany the passage of intense low pressure centres north of Edson. It is probable that similar winds occur in other, but unpopulated, valleys of the foothills.

Non-tornado thunderstorm winds are common and are sometimes accompanied by tornadoes. In fact, with the available data, it is often difficult to distinguish between a weak or moderate tornado and a thunderstorm downburst. The most destructive thunderstorm winds appear to have occurred over open prairie in eastern Alberta and in Saskatchewan. Examples are the storms of 1923 June 30 in the Rosetown, Saskatchewan area (Mosley 1984), and 1918 July 30, in the Wainwright, Alberta area.

Fire-produced updrafts often lead to the formation of whirlwinds or fire devils. At times, the associated winds are strong enough to tear mature evergreen trees from the earth. In June 1906, near Parkland, Alberta, a house with occupants was lifted and carried a few hundred metres by what may have been a fire devil or tornado that moved ahead of an approaching grass fire front (Nanton and District Historical Society 1975).

This study included all storms identified as tornadoes with no lower limit to the severity of damage. However, "other destructive windstorms" were included only if "significant damage" occurred. "Significant damage" meant removal of roofs, flattening of walls, or the removal from foundations of small buildings such as grain bins, sheds, or garages. Removal of shingles or other roofing material, window breakage, or toppling of scattered telephone poles, trees, or signs were not considered to be significant.

## 4. TORNADO IDENTIFICATION

The criteria used for identification of tornadoes were dictated by the information content of newspaper reports and community history descriptions. The following six criteria were adopted and applied to the accounts of eyewitnesses or residents in or near the area of damage.

1. Funnel cloud observed;
2. Evidence of rotational motion;
3. Severe wind or pressure effects, such as:
    - Objects lifted from wells;

  - Houses lifted from foundations;
  - Water lifted from ponds, lakes, or rivers;
  - Missile damage;
  - Severe twisting attributable to suction vortices;
  - Fish, frogs falling from the sky;
  - Fowl defeathered, horse hair removed;
  - Sickles removed from mowers, railroad tracks torn and bent or twisted; and
  - Explosive effects.

4. Unusual lift or unusual lift and scatter, such as:
    - Sods torn up;
    - Wooden sidewalks lifted and carried away; and
    - Debris observed to be "floating" in the air.
5. Storm called tornado, twister, whirlwind, miniature cyclone, or waterspout.
6. Wind described as small entity.

Criterion 5 was applied with caution. The word tornado was sometimes misused when applied second or third hand. The terms miniature cyclone, baby cyclone, small cyclone, small tornado, miniature tornado, and baby tornado were often used to separate a tornado from a "cyclone" which, for many people, denotes any destructive windstorm. The term whirlwind was used for tornadoes much more frequently near the beginning of the 20th century than at present. In almost all cases, two or more of the above criteria were satisfied and it was not unusual for four or five of the six criteria to be satisfied for individual tornados. Nevertheless, it is likely that some storms identified as tornadoes were not, in fact, tornados and that some "other destructive windstorms" were tornados.

## 5. DESTRUCTIVE WINDSTORM FREQUENCIES

The total data sample available for analysis is summarized in Table 1. Table 1 includes storms from 1879 to 1984 in Alberta and from 1879 to 1960 in Saskatchewan. It is expected that the data sample will increase

**Table 1.** Total windstorm data sample.

| Events | Storm Days | Tornado Days | Tornadoes |
|---|---|---|---|
| 2360 | 1246 | 740 | 1079 |

significantly when a search through additional, readily-available data sources has been completed.

For purposes of interprovincial comparisons, windstorms prior to 1910 were omitted because of major differences in rural population density in large areas of Alberta and Saskatchewan. Most frequency tabulations were terminated in 1960 because, in Saskatchewan, damage assessments were incomplete for post-1960 storms. The data sample for 1910 to 1960 is summarized in **Table 2**. The total numbers are remarkably similar for the two provinces. Individual farms were the primary sources of data in this study. Therefore, the interprovincial differences could be accounted for by the fact that the number of farms in Saskatchewan exceeded that in Alberta by 25 to 30 percent in the interval 1910 to 1960. The numbers of storm days were nearly identical in the two provinces and averaged 9 per year.

According to Court (1970), complete tornado reporting requires a minimum observer network averaging at least several persons per square mile. Such networks are found only in urban areas of Alberta and Saskatchewan. **Table 3** lists the numbers of tornadoes known to have occurred in most of the large urban areas of both provinces together with the average populated area of each city over the period 1910 to 1960. When extrapolated to a constant reference area, the average tornado frequency was found to be 13.5 per 10 000 $km^2$ per year. This astonishing number exceeds the average frequency of 3.2 tornadoes per 10 000 $km^2$ per year, averaged for the period 1953 to 1974 for the state of Oklahoma (Kessler and Lee 1976), and is a shocking reminder of how sensitive tornado statistics are to population density. The problem results from relatively large numbers of extremely weak

Table 2. Comparative totals of windstorms in Alberta and Saskatchewan from 1910 to 1960.

| Province | Events | Storm Days | Tornado Days | Tornadoes |
|---|---|---|---|---|
| Saskatchewan | 1035 | 467 | 278 | 426 |
| Alberta | 753 | 452 | 234 | 308 |

Table 3. Tornado frequencies in urban Alberta and Saskatchewan from 1910 to 1960.

| City | Average Area ($km^2$) | No. of Tornadoes | No. of Tornadoes per 10 000 $km^2$ |
|---|---|---|---|
| Edmonton | 114 | 5 | 440 |
| Calgary | 110 | 2 | 180 |
| Regina | 76 | 7 | 920 |
| Saskatoon | 63 | 5 | 790 |
| Moose Jaw | 35 | 6 | 1710 |
| Lethbridge | 29 | 2 | 690 |
| Medicine Hat | 22 | 4 | 1820 |
| Average | | | 690 |

tornadoes for which damage is limited to very small areas and short time periods. It is concluded that complete tornado frequencies are reliable only within urban areas. In rural areas, the frequencies of past tornadoes should increase in reliability with increases in intensity, path length, and path width. In other words, despite numerous sampling problems, it is reasonable to place more confidence in the statistics of moderately intense tornadoes than in those from weak tornadoes or all tornadoes combined.

## 6. WINDSTORM DEATHS, INJURIES, AND PROPERTY LOSSES

The windstorms reported in Table 1 were responsible for serious injuries and loss of life and property. Because some buildings are more susceptible to wind damage than others, they were subdivided into (a) "substantial" buildings, (b) large barns and rinks, and (c) other buildings. "Substantial" buildings included houses (not including shacks, bunkhouses, cottages, trailers, or mobile homes), churches, schools, community halls, and industrial and commercial buildings. Large barns and ice rinks were listed separately because of their relatively weak construction and large surface area exposed to wind. The impact of windstorms of Table 1 on life and property is summarized in Table 4. Comparative statistics on the impact of tornadoes in Alberta and Saskatchewan for the period 1910 to 1960 are shown in Table 5. Similar data for "other destructive windstorms" are listed in Table 6. From a comparison of Tables 5 and 6 with Table 2, it is clear that total per-storm deaths, injuries, and numbers of buildings destroyed or severely damaged were considerably higher in Saskatchewan than in Alberta even when differences in the numbers of farms are taken into account. It should be noted, however, that 28 deaths and at least 80 injuries resulted from a single tornado at Regina, Saskatchewan in June 1912. The fact that large interprovincial differences are not evident in deaths from non-tornado windstorms is attributed to many of these deaths being due to falling trees or signs and to winds that arose when people were in vulnerable locations on towers or rooftops. The total deaths, injuries, and number of substantial buildings destroyed or severely damaged per tornado in both provinces exceeded similar totals per non-tornado windstorm. For comparison with Tables 5 and 6,

Table 4. Deaths, injuries, and significant building loss or damage that resulted from the windstorms of Table 1 in Alberta and Saskatchewan.

| Deaths | Persons Injured | Substantial Buildings | Large Barns, Rinks | Other Buildings |
|---|---|---|---|---|
| 144 | 502 | 1872 | 2198 | 6164 |

Table 5. Deaths, injuries, and significant building loss or damage resulting form the tornados of Table 2 in Alberta and Saskatchewan from 1910 to 1960.

| Province | Deaths | Persons Injured | Substantial Buildings | Large Barns, Rinks | Other Buildings |
|---|---|---|---|---|---|
| Saskatchewan | 64 | 286 | 761 | 776 | 2007 |
| Alberta | 16 | 85 | 279 | 226 | 621 |

Table 6. Deaths, injuries, and significant building loss or damage resulting from the non-tornado windstorms of Table 2 in Alberta and Saskatchewan from 1910 to 1960.

| Province | Deaths | Persons Injured | Substantial Buildings | Large Barns, Rinks | Other Buildings |
|---|---|---|---|---|---|
| Saskatchewan | 14 | 54 | 358 | 852 | 2232 |
| Alberta | 22 | 38 | 156 | 187 | 563 |

the number of known deaths due to lightning in the period 1910 to 1960 was 128 in Saskatchewan and 118 in Alberta. Note, however, that in both provinces the death rate from lightning has dropped appreciably since about 1950.

## 7. SEASONAL VARIATIONS IN TORNADO FREQUENCIES

Although tornadoes are known to have occurred as early as February and as late as November in Alberta and Saskatchewan, the vast majority occurred in June, July and August; these are months of most frequent thunder and hailstorms. Frequencies for 14-day periods are shown in **Figure 1** for all tornadoes in both provinces and for a subset of tornadoes which "demolished" at least one substantial building. The definition of a "substantial" building was given in Section 6. The term "demolished" was taken to mean that the entire roof and at least two outer walls were removed from the building. No significant difference in seasonal variation was found between Alberta and Saskatchewan. Ninety percent of all tornadoes that demolished at least one substantial building occurred between June 1 and August 15. The monthly frequencies for all tornadoes and for the most intense tornadoes were similar except that intense tornadoes were less frequent than weak tornadoes in April and May.

## 8. LONG-TERM VARIATIONS IN TORNADO FREQUENCIES

Annual tornado frequencies from 1890 to 1984 in Alberta and from 1890 to 1982 in Saskatchewan are shown in **Figure 2**. Saskatchewan tornado frequencies for the years 1961 to 1982 were taken from Raddatz et al. (1983). These figures were not included in Tables 1 to 6 because analyses of damage from the storms are incomplete. Figure 2 shows the expected increase in frequencies with the rapid rise in rural population density that took place between 1890 and 1910 as well as some evidence of increased frequencies after 1960. The latter trend is attributed to improved observation and reporting of tornadoes in recent years. The annual frequencies ranged from zero to between 20 and 30 in peak years. Annual frequencies of tornadoes that demolished at least one substantial building are shown in **Figure 3**. In this and subsequent figures, five-year totals ending at the years shown on the graphs

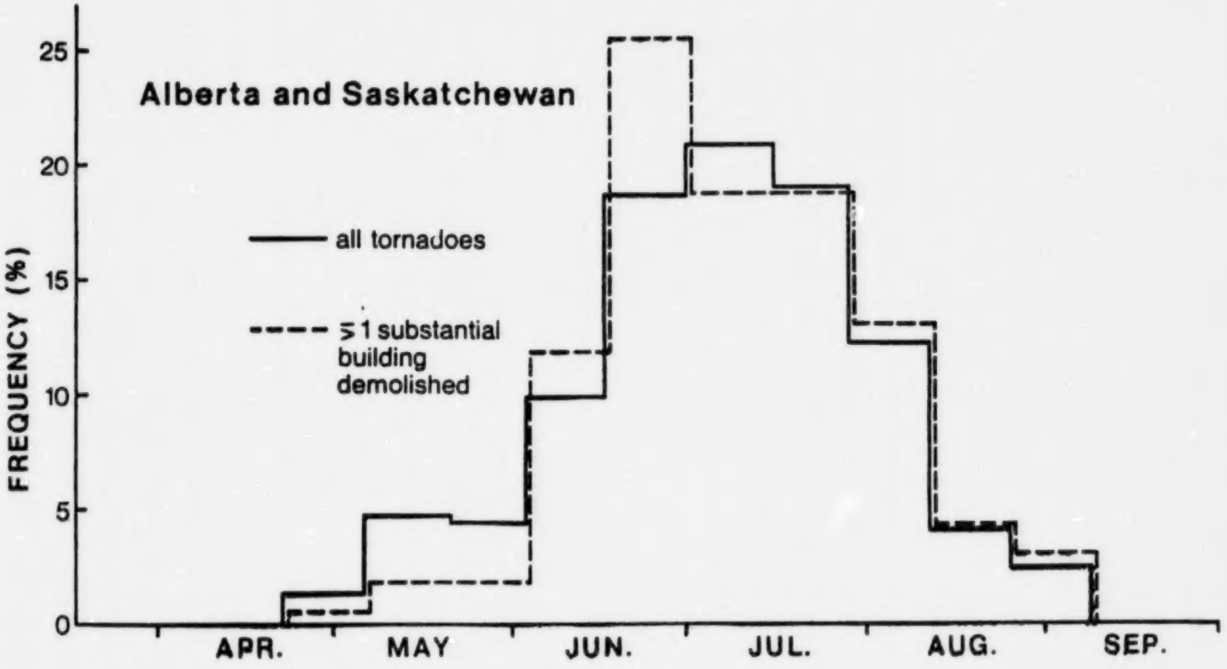

Figure 1. Frequencies of tornadoes for consecutive 14-day periods in Alberta and Saskatchewan, 1910 to 1960.

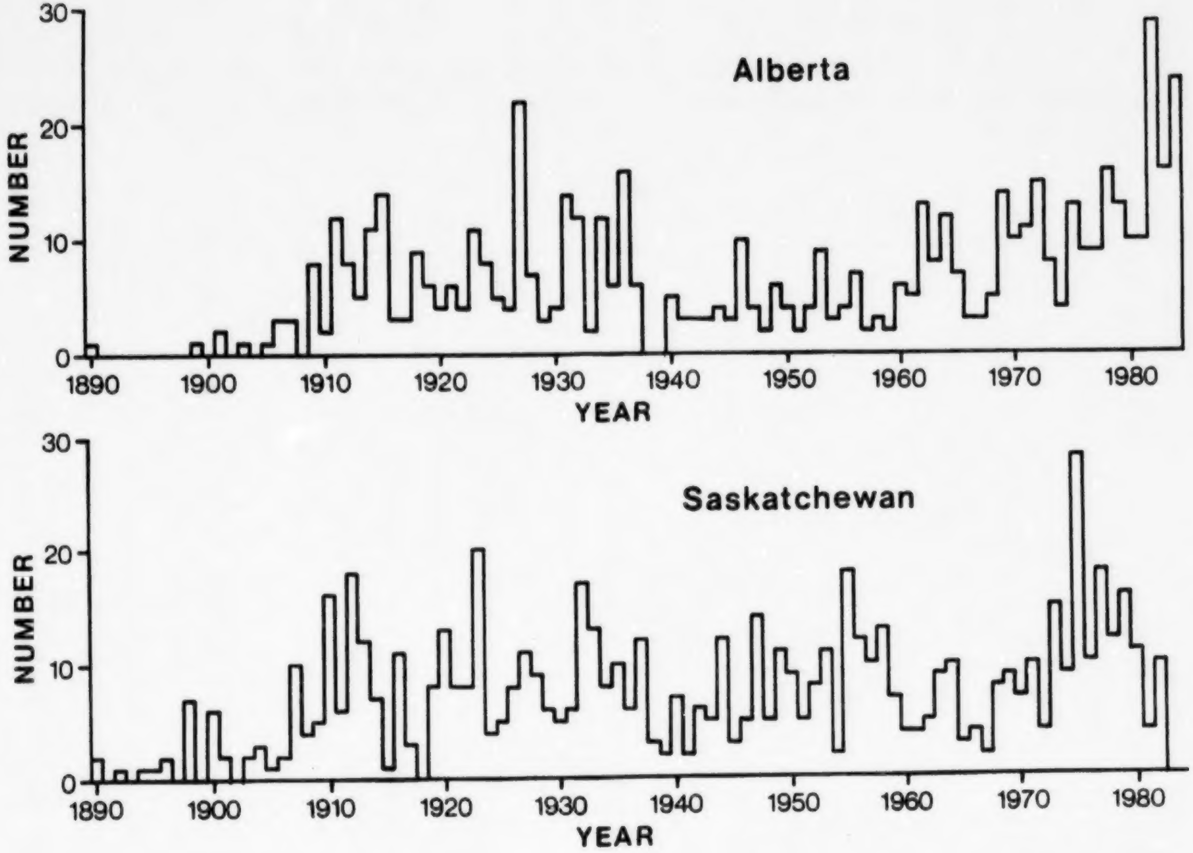

Figure 2. Annual frequencies of all known tornadoes in Alberta and Saskatchewan.

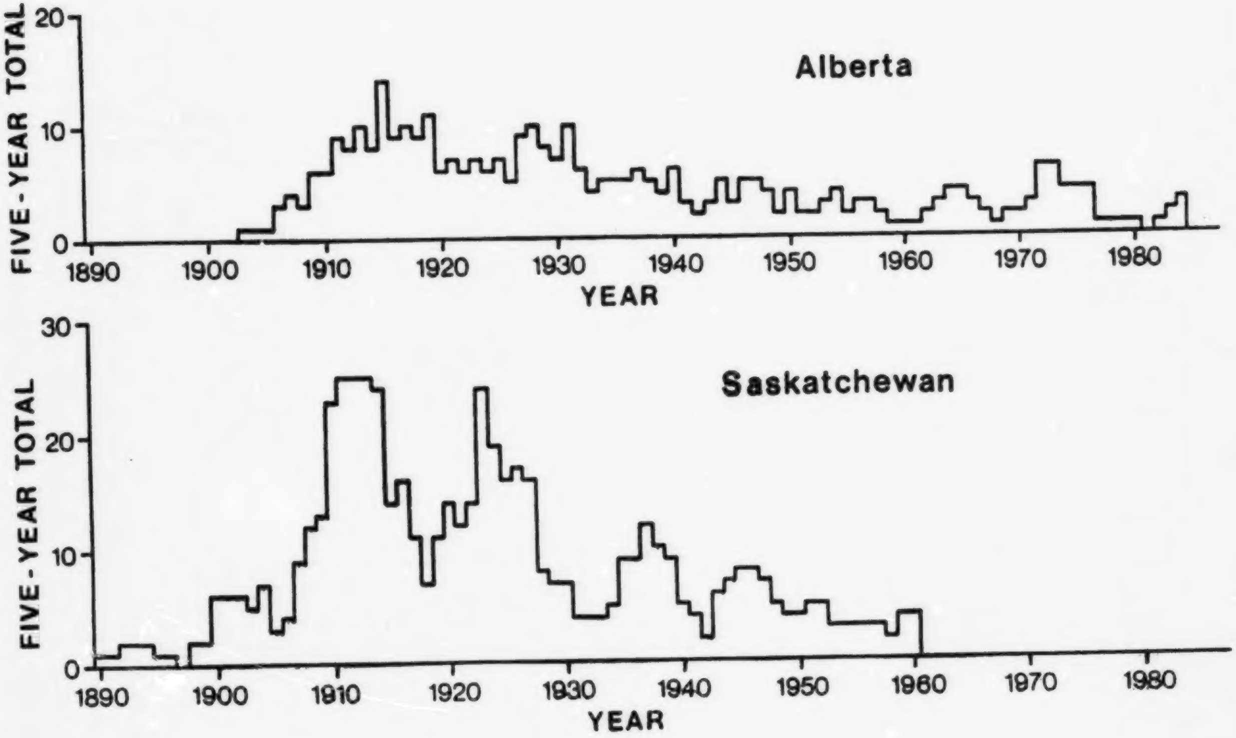

Figure 3. Annual frequencies of tornadoes that demolished at least one substantial building. Five-year totals ending at indicated years.

were used because of the smaller number of storms available for study. By comparing Figures 2 and 3, it is evident that the increased frequencies of tornadoes in Alberta after about 1960 resulted from increased reports of weak tornadoes only. This supports the idea that improved tornado reporting was responsible for their apparent recent increase in numbers.

Figure 3 also shows a period of relatively high frequencies from about 1910 to 1930 in both provinces. Was the maximum the result of a real climatic change or did it result from the fact that rural population was at its maximum in many parts of central and southern Alberta and Saskatchewan in these years? In an attempt to answer this important question, a sub-sample of tornadoes that not only demolished at least one substantial building but also struck a hamlet or larger settlement was selected. The density and distribution of hamlets, villages, and towns have changed little since the 1910 to 1915 period. Therefore, the number of tornadoes based on these criteria should be relatively free of observation and reporting bias.

The results of **Figure 4** shows evidence of a rather pronounced downward trend in tornado frequency between 1915 and 1940. Little can be said about trends before 1915 because new settlement centres were created at a rapid rate before that time. Therefore, the apparent downward trend in major tornado frequencies may have commenced before 1915.

The frequencies of non-tornado windstorms that demolished at least one substantial building and struck a hamlet or larger settlement are shown in **Figure 5**. The number of storms that met these requirements was very small and it would be inappropriate to discuss time trends except to note the similarities between Figures 4 and 5 for tornado and non-tornado windstorms.

## 9. SPATIAL VARIATIONS IN TORNADO FREQUENCIES

The location of all known tornadoes that demolished at least one substantial building in Alberta and Saskatchewan in the years 1910 to 1960 are shown in **Figure 6**. Also shown in this figure are the approximate boundaries of populated (agricultural) regions of the provinces. It is of course highly probable that similar tornadoes have passed unseen outside these boundaries and that major damage to the landscape has gone unreported.

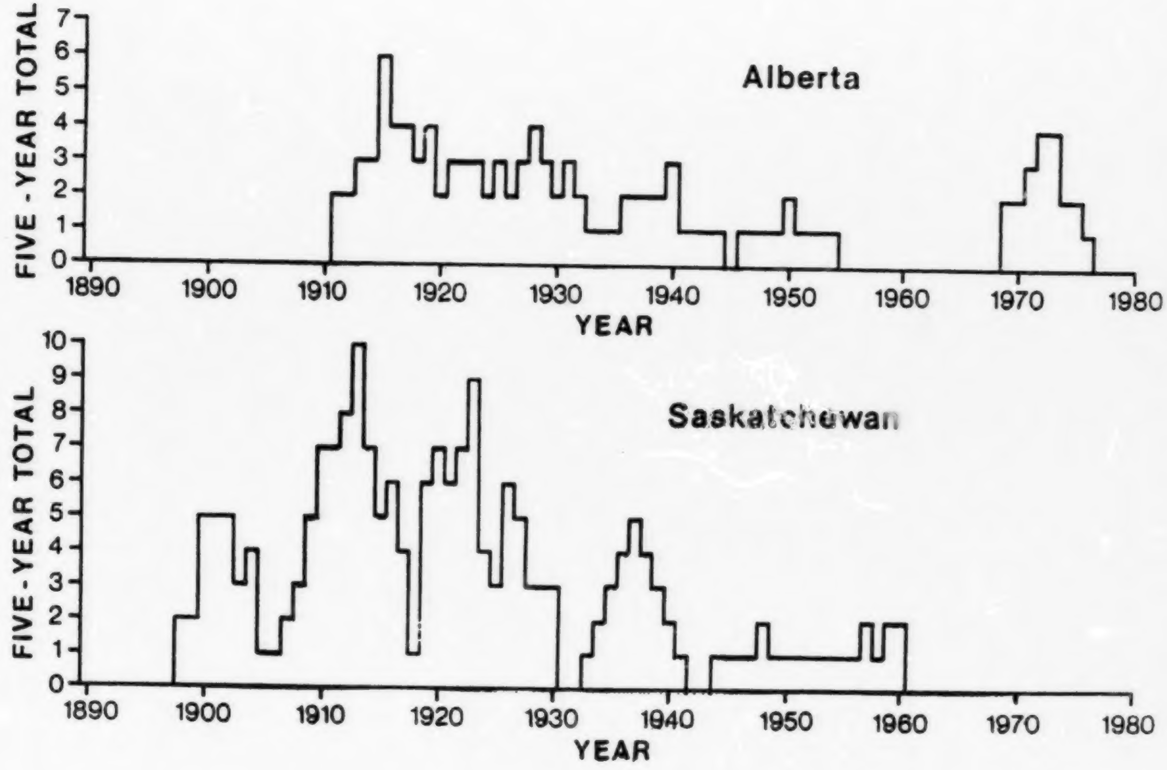

Figure 4. Annual frequencies of tornadoes that demolished at least one substantial building and struck a hamlet or larger settlement. Five-year totals ending at indicated years.

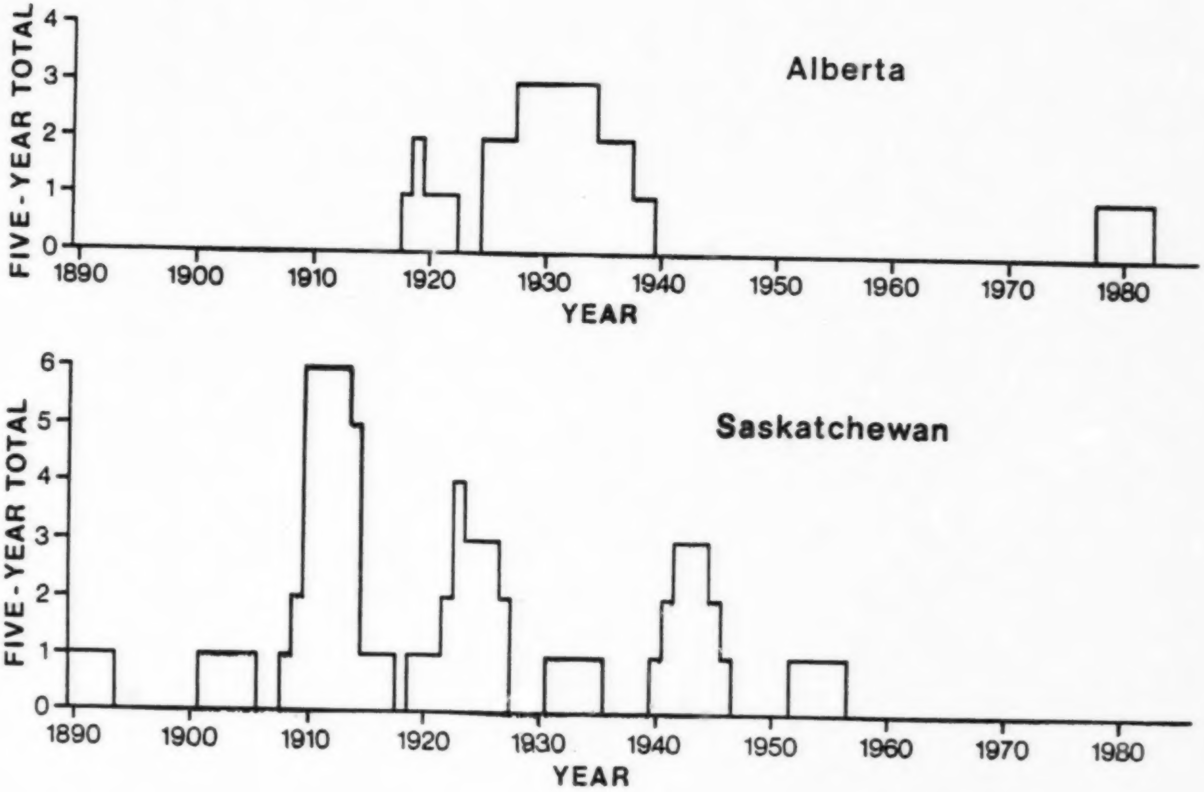

Figure 5. Annual frequencies of non-tornado windstorms that demolished at least one substantial building and struck a hamlet or larger settlement. Five-year totals ending at indicated years.

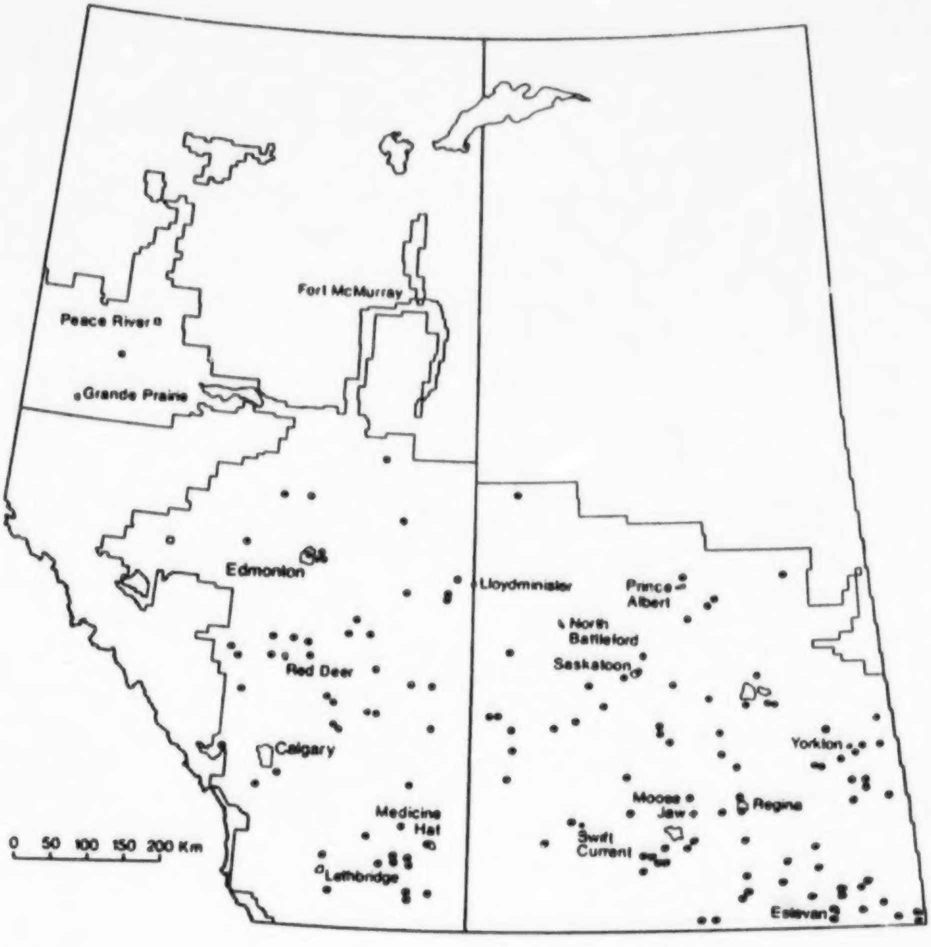
Fort McMurray
Peace River
Grande Prairie
Edmonton
Lloydminster
Prince Albert
North Battleford
Saskatoon
Red Deer
Calgary
Yorkton
Moose Jaw
Regina
Medicine Hat
Swift Current
Lethbridge
Estevan
0 50 100 150 200 Km

Figure 6. Locations of tornadoes that demolished at least one substantial building in Alberta and Saskatchewan, 1910 to 1960.

The events shown in Figure 6 were converted to frequencies per 10 000 $km^2$ and mapped (**Figure** 7). A major weakness of both Figures 6 and 7 is the possibility of sampling errors. Certain regions such as southwestern Saskatchewan, including the Cypress Hills, and southeastern Alberta, have much lower rural population densities than other parts of Alberta and Saskatchewan. The low frequencies shown in those regions may not be real. However, the region of relatively low frequencies which appears to separate higher frequencies in southeastern Saskatchewan from a band of relatively high frequencies in central and southern Alberta is thought to be real because rural population densities west and southwest of Saskatoon were not particularly low in the period of study. It is tentatively concluded that a band of relatively high, moderate-intensity, tornado frequencies (about 0.1 per 10 000 $km^2$ per year) existed in the period 1910 to 1960 from near Edmonton south-southeastward to west of Medicine Hat. This band appears to have been separated from the higher frequency maximum that extended from near Moose Jaw toward Estevan, Saskatchewan. The former band was more or less parallel to the Rocky Mountains and was centred 250 to 300 km east of the Continental Divide. More research is needed to explore the relationship, if any, between this area of moderate-intensity tornadoes and the life cycle of thunderstorms and convective complexes that often form in the foothills and move eastward toward the prairies.

## 10. LIST OF FATAL TORNADOES

**Tables** 7 and **8** list all known tornadoes that resulted in human fatalities in Alberta and Saskatchewan, respectively. These are not necessarily the most severe or largest tornadoes that have occurred. The two tables update and correct lists originally published by Lowe and McKay (1962) and are subject to revision as new information becomes available.

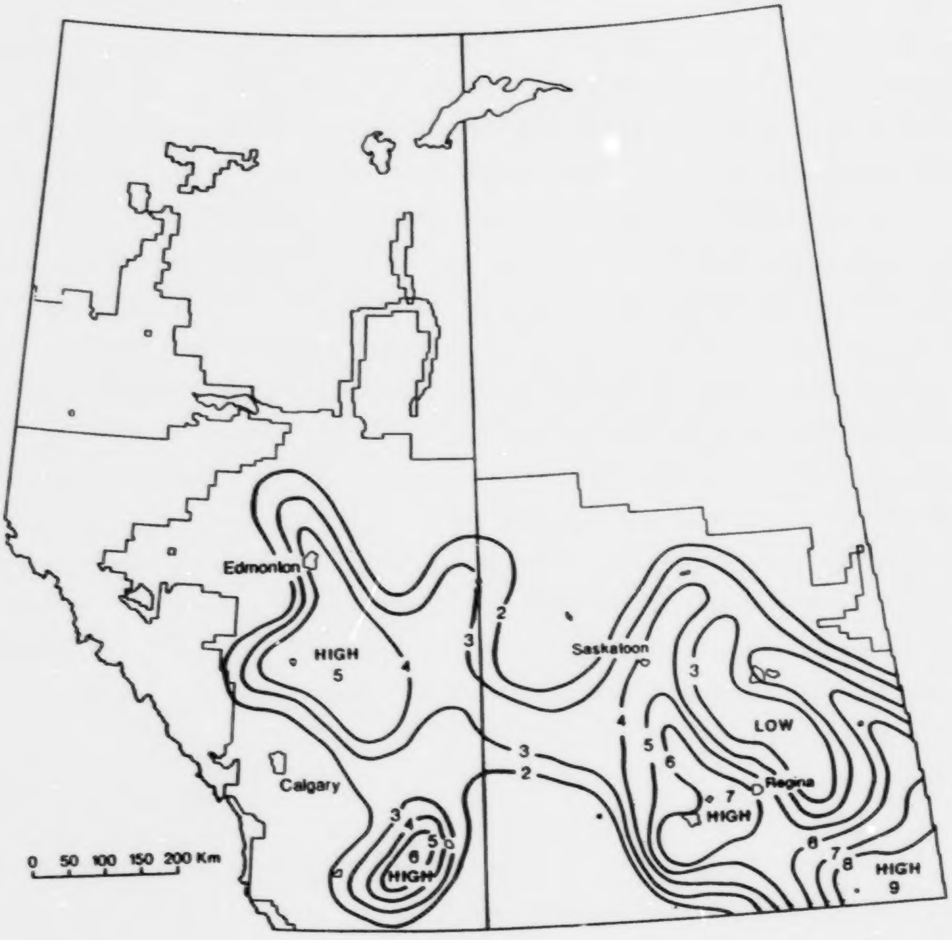
Edmonton
HIGH
5
4
3
2
Saskatoon
LOW
Regina
7
HIGH
6
5
Calgary
HIGH
8
7
HIGH
9
0 50 100 150 200 Km

Figure 7. Number of tornadoes per 10 000 km$^2$ in the 51-year period 1910 to 1960 in Alberta and Saskatchewan. Only those tornadoes that demolished at least one building are included.

Table 7. Fatal tornadoes in Alberta.

| Year | Date | Nearest Settlement | Fatalities | Persons Injured |
|---|---|---|---|---|
| 1879 | May 16 | Saddle Lake | 1 | -- |
| 1907 | August 14 | Wainwright | 3 | -- |
| 1910 | July | Sibbald | 1 | -- |
| 1912 | June | Oyen | 1 | -- |
| 1915 | June 25 | Grassy Lake | 4 | 11 |
| 1918 | July 30 | Tolland | 1 | 3 |
| 1919 | June 21 | Empress | 1 | 1 |
| 1927 | July 8 | Wetaskiwin | 3 | -- |
| 1950 | August 11 | Morley | 4 | 6 |
| 1960 | August 3 | Travers Dam | 1 | 3 |
| 1961 | July 7 | Gooseberry Lake | 1 | 1 |
| 1972 | July 28 | Bawlf | 1 | 2 |
| 1984 | June 29 | Richmond Park | 1 | 1 |

Table 8. Fatal tornadoes in Saskatchewan.

| Year | Date | Nearest Settlement | Fatalities | Persons Injured |
|---|---|---|---|---|
| 1898 | June 20 | Benson | 1 | -- |
| 1900 | August 28 | Wapella | 5 (?) | 2 |
| 1907 | August 8 | Last Mountain Lake | 1 | 7 |
| 1907 | August 8 | Zealandia | 1 | -- |
| 1908 | July 28 | Fillmore | 1 | 7 |
| 1909 | July 1 | Storthoaks (Ste. Antoine) | 4+ | 28 |
| 1910 | June 23 | Palmer | 3 | 8 |
| 1910 | June 27 | Weyburn | 1 | 1 |
| 1910 | July 3 | Grandora | 1 | 1 |
| 1912 | June 30 | Regina | 28 | 80+ |
| 1913 | August 14 | Ogema | 2 | -- |
| 1916 | August 28 | Atwater | 1 | 4+ |
| 1919 | June 27 | Quill Lake | 2 | 2 |
| 1919 | June 27 | Lanigan | 1 | -- |
| 1920 | July 22 | Benson, Lampman | 2 | 9 |
| 1920 | July 22 | Frobisher, Alameda | 3 | 20 |
| 1923 | June 16 | Sceptre | 1 | -- |
| 1923 | June 16 | Rosetown | 1 | 3 |
| 1923 | July 7 | McGee | 1 | 4 |
| 1924 | July | Constance | 1 | -- |
| 1926 | July 14 | Waldron | 2 | 5 |
| 1927 | June 18 | Mozart | 1 | 6 |
| 1932 | May 31 | Aberdeen | 1 | -- |
| 1933 | June 17 | Saskatoon | 1 | -- |
| 1935 | July 1 | Benson | 1 | 2 |
| 1935 | July 6 | Smiley | 2 | -- |
| 1935 | July 28 | Ile a la Crosse | 1 | 3+ |
| 1944 | July 1 | Lebret | 4 | -- |
| 1944 | August 9 | Kamsack | 3 | 42 |
| 1963 | June 29 | Spy Hill | 1 | 2 |
| 1976 | June 3 | Davidson | 1 | 15 |
| 1979 | July 10 | Glasnevin | 1 | -- |

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# PART II: SUMMARY REPORT ON THE WORKSHOP SESSIONS

## ACKNOWLEDGMENTS

The success of the workshops is attributed primarily to the facilitators who guided the discussions; the recorders who documented the discussions; and the participants who provided invaluable input to the group deliberations. The development and organization of the workshop agenda were difficult tasks because of the concerns for the limited time available for (1) discussion and identification of issues and recommendations; and (2) achieving consensus on priority issues. To this end, the efforts of Mr. Tom Grauman of the Edmonton Social Planning Council in assisting the Steering Committee in formulating the workshop agenda and leading a training session for the facilitators are gratefully acknowledged.

## 1. INTRODUCTION

These workshops, the first held in Alberta related to climatic variability and change, were intended to provide the participants at the Symposium with the opportunity to:

1. Identify issues/concerns and requirements pertinent to the impacts of climate on industry and the resource sectors;
2. Prioritize these issues/concerns and requirements in order of importance; and
3. Formulate recommendations for future research and monitoring and other related initiatives to address these priorities.

The workshops were designed to cover, in addition to science and technology, matters such as communication and policy. Six concurrent workshops were held each dealing with a different, although to some degree, interrelated topic:

**Workshop 1** - Are the causes of climatic variability and change known?

**Workshop 2** - Planning for climatic variability and change - who cares?

**Workshop 3** - Is climate effectively used in our resource sectors?

**Workshop 4** - Can we quantify the links between climate and our resources?

**Workshop 5** - Is there sufficient communication regarding climate and its impacts?

**Workshop 6** - What are the socio-economic impacts of climatic variability and change?

These topics were used primarily by the facilitators to guide the discussions. The information presented and questions raised during the Technical Session of the Symposium provided the impetus for discussion. Each workshop was responsible for identifying priority issues pertinent to their respective topic. The issues were then discussed and prioritized. The issues from each workshop were reviewed by the Steering Committee and facilitators. Issues were consolidated and reworded into specific questions for each workshop to discuss in further detail and formulate specific recommendations to address each of them. This exercise clarified the main issues and reduced them to a manageable number. A summary of each of the workshop deliberations is provided in the ensuing section.

## 2. SUMMARY OF WORKSHOP DELIBERATIONS

### 2.1 WORKSHOP 1: ARE THE CAUSES OF CLIMATIC VARIABILITY AND CHANGE KNOWN?

Facilitator: R.G. Humphries, Alberta Research Council
Recorder: F.D. Barlow, Alberta Research Council

This workshop addressed modelling climatic variability and its impacts. The participants were encouraged to discuss their concerns and needs regarding: (1) understanding the causes of climatic variability and change; (2) mechanisms to equate these causes to quantifiable changes in climate; (3) regional modelling of climatic variability and its impacts; and (4) associated research needs.

The group briefly reviewed the papers that were presented during the Technical Session. These papers served to focus attention on the issues that were of greatest concern. One item that everyone commented on was ethics which was mentioned by R. Lawford in his presentation. We must be ethically correct and not overstate the case. In other words, scientists should be careful not to misrepresent climate related issues to the policy makers.

The issues identified by the group were broad in scope and often wandered outside the specific topic listed for Workshop 1. Given the eclectic interests of the group, it was decided not to constrain the issues provided they did not overlap too much with the other workshop topics. Sixteen questions were identified by the group but only the five that received highest priority by the group are listed:

1. **Are the cause and trend of climatic change (warming?) identified?** This question alluded to a general lack of confidence in global climate models. The group felt we needed to better understand the accuracy of General Circulation Models

(GCMs). It was not known how much one could trust GCMs, whether they can be adequately tested and if so, are they tested.

2. **Do existing data sets meet the needs of users?** This question addressed the problem of identifying what climate data are available, the quality of the data, the compatibility of the data with other data sets and with the analysis that is required, the misuse of data by unskilled users, the accessibility of the data, and documentation of the data.
3. **Are feedback mechanisms sufficiently understood and properly integrated into climate prediction models?** The group felt that the answer to this question was "no" and hence needed to be addressed.
4. **Are models adequately simulating the current climate?** This question does not necessarily require all aspects of the current climate to be simulated; but a judge of the validity of a model is how well it handles the current climate.
5. **Is climatic variability properly understood and used on all temporal and spatial scales?** Since climatic variability seems to be the norm, it is important to know how well variability is handled.

These five questions were considered and four recommendations made:

1. Efforts should be directed into mesoscale research to improve parameterization in GCMs, to improve mesoscale models for use in GCMs, and to develop more highly detailed models to test highly parameterized models within GCMs.
2. An effort should be made to at least maintain and preferably increase monitoring of climate related parameters to detect climate trends. This should include parameters such as vegetation cover. It was recognized that Canada has a special position because of its northern area. Specifically, it was recommended that a more comprehensive "western Canadian" climate station network should be established which would reflect the interdisciplinary requirements of the various user groups.

3. Air-sea interaction research should be expanded and an effort made to link oceans to climate models.
4. An effort should be made to improve regional, national, and international cooperation for the purposes of exchanging information (e.g., data to help develop and test climate and impact models).

## 2.2 WORKSHOP 2: PLANNING FOR CLIMATIC VARIABILITY AND CHANGE - WHO CARES?

Facilitator: A.J. Malinauskas, Canadian Climate Centre
Recorder: P. Papirnik, Alberta Environment

Four issues deserving further attention were identified by the participants:

1. **Is there a need for national and international strategies to control anthropogenic chemical additions to the atmosphere?** It was recognized that national and international energy policies have a direct impact on the rate of $CO_2$ emissions and that other policies (or lack of them) have similar implications for emissions of other "greenhouse gases". Past actions to control additions/alterations to the chemical composition of the atmosphere (e.g., sulphur dioxide emissions) and current international initiatives (Ozone Protocol) were seen as steps in the right direction.
2. **Do planners and policy makers have sufficient information and understanding of climate issues and their implications for society to enable the development and implementation of appropriate responses?** The focus of this issue was on the adequacy of information currently available to planners and policy makers. The scientific uncertainty relating to the future rate of man-made $CO_2$ (and other greenhouse gas) emissions, inadequacies (parameterizations, feedback mechanisms, and grid scale) of atmospheric general circulation models, and the lack of

hard evidence on the rate, magnitude, and regional distribution of climatic change were seen as major impediments to the development of policy/planning response. In spite of these constraints, it was felt that some economic sectors could and should factor the available information into their long-term planning processes.

3. **Does the climate community have a sufficient understanding of the needs of policy makers and resource managers?** Discussion on this issue centered on the need for improved communication between providers and users of climate information. The providers of information have identified some potential implications of climatic change for society and the economy and have been proponents of the need for action to mitigate adverse consequences and take advantage of possible opportunities. Workshop participants felt, however, that more effort was needed to identify the specific information needs required by planners/policy makers (e.g., What type of information is needed?; in what format?; to what degree of accuracy/certainty?).
4. **Is there a need to priorize the selection of economic sectors for analysis?** There was agreement that the prospect of climatic change was of more urgency for some economic sectors than others and that efforts be made to identify priority sectors and develop plans to address their needs. Those identified by participants as requiring immediate attention included:
   a. Water Resources
      - security of supply (municipal water use; agricultural requirements);

   b. Energy Use
      - impact on future hydro-electric power generation;

   c. Forestry
      - impact on (incidence/frequency) of forest firest; insects and disease; productivity; reforestation decisions; and

   d. Large-scale and long-term capital projects.

Three recommendations, arising from the issues previously identified, were formulated:

1. Federal and provincial governments should expand their monitoring programs and continue to promote control strategies. Development of further control strategies was endorsed. Expansion of monitoring programs was felt necessary both from the standpoint of research needs and for compliance (to control) measures.
2. Provincial and Territorial Climate Advisory Committees should develop plans to promote the communication of current climate issues and their implications for society; the plan should include a mechanism to determine the needs of policy makers and resource managers.
3. Provincial and Territorial Climate Advisory Committees should identify priority economic sectors and develop research proposals to address their most immediate needs with particular respect to the possible effects of climatic change and variability.

The last two recommendations followed from the issues (What are the problems?; What should be done?; Who should do it?; How should it be done?). It was felt that since the membership of the Provincial/Territorial Climate Advisory Committees includes representation from federal and provincial agencies as well as universities and, in some cases, the private sector that these committees were in the most appropriate position to address the needs especially from a regional perspective.

## 2.3 WORKSHOP 3: IS CLIMATE EFFECTIVELY USED IN OUR RESOURCE SECTORS?

Facilitator: P. Dzikowski, Alberta Agriculture
Recorder: B. Thomson, Atmospheric Environment Service

Workshop participants addressed the question: "Is climate effectively used in our resource sector?". There was discussion about the climate-related data and information used and/or required by industry or the resource sectors. In most cases, there was little use of climate information but a requirement for it. It was suggested the participants may want to comment on:

1. How they incorporate climate into their operations;
2. Adequacy of the available information; and
3. Their requirements pertaining to climatic variability/change such as forecasting climatic variability/change and its impacts.

There was much pondering about the question itself. Discussion started off by going around the table and each participant stating an opinion or making a comment. The participants were quite a diverse group within the resource sector. Although there were quite unique aspects to each of their comments, there were several key issues that were relevant to each resource sector. Some of these common concerns were about data availability, poor understanding of complex systems, poor communication between modellers and application people, and how existing variability can be better understood. The various opinions and concerns were grouped to create a manageable number of key issues. The main concerns or issues identified by this workshop were:

1. The Climate-Resource Base Link. The link between climate and the resource base is known in general terms for large areas and for longer time periods, but it is not understood well enough for detailed planning. Concern was expressed about application models, which describe the link between climate and responses in the resource sectors. It was felt that problems with the reliability, availability and/or accessibility of application models restrict their use. A common limitation of many application models is they present information about mean conditions, when what is also needed in the resource sector is information about risk. In a nutshell, there is difficulty in using models, which require simple inputs, to deal with complex systems. An example of an application model is either a crop yield or forestry productivity model.
2. Communication (Education) Gap. The group felt that not enough is known by users about the availability of application models, or about their strengths or weaknesses. This communication (or education) gap applies equally to general circulation models,

impact assessment models, and to information about the types of climate data available. User needs have to be identified and shared with those developing application models. A case in point is to get probabilities of events out of models, rather than mean values. There is a need to pay attention to scale in both space and time. General products suitable at a national scale are clearly not suited for dealing meaningfully with small areas. Similarly, long-term means, or even an extreme value, do not present usable data on the risk that climate poses to any given resource sector. As user requirements grow in complexity, climate analysis tools must keep pace and match both temporal and spatial requirements wherever possible.

3. Climate Data Suitability. Concerns were raised about the pertinence of existing climate data in terms of spatial and temporal requirements of users. As the need grows for more detailed information, there is concern about the adequacy of existing data sets. This concern applies not only to station density, but also to the measurement interval. The question was raised about the role of technology such as weather radar and satellite imagery in providing new sources of data. The concern of scale emerged again with regards to whether mismatches of scale were occurring between the climate information needed (smaller areas) and that available (larger areas).
4. Climatic Variability. It was generally recognized that naturally occurring climatic variability can create havoc in the resource sector. Yet there is a lack of information available to help resource managers understand climatic variability in order to better manage the resource. Normals present a seemingly steady state picture with some sort of variation about the mean, but such information does little to indicate the risk that climate poses to any given resource sector. It was widely felt that if the resource sector could better cope with climatic variability, then it could also better cope with climatic change. The prospect of having useful information about climatic variability

for the next few years is much more appealing than trying to get information about what may be occurring in 50 to 100 years time. That is not to say that future climates are not important, rather, the fact that we have to live with the present climate and its variability is also important.

The concerns identified were formulated into tne following questions which were presented to the working group.

1. Can we use available climate data to model responses of the physical resource sector?
2. Is there a communication gap between users and providers of climatic information?
3. Do existing (climate) data sets meet the needs of users?
4. Is there a greater need for information on climatic variability than for long-term climatic change?

Three recommendations were synthesized from the concerns identified:

1. State-of-the-Art Report on Application Models. The Canadian Climate Program should undertake to:
   a. Prepare a state-of-the-art report on application models to inventory and evaluate their capabilities and limitations by (1) resource sector; and (2) scale; both temporal and spatial;
   b. Inventory all available climate data; and
   c. Determine in consultation with Climate Advisory Committees how (a) and (b) compare.

   This recommendation combines the two concerns about (1) the lack of information about application models which describe the response of the resource sector to climate and (2) the adequacy of available climate data to drive them. This helps assess the availability of tools to resolve identified user needs.
2. Communication/Education. Communication, in the broadest sense, between users and suppliers of information needs to be improved. In order to accomplish this, a two-part strategy was suggested:

a. Atmospheric Environment Service develop a marketing strategy to promote the availability and use of climate data. It is expected that the identification of user needs would be an integral part of such a marketing strategy.

b. More effort be directed to educate users of climate data about climatology, and educate providers of information about application of climate data. This would be a role for universities, professional associations, and user groups.

3. More Emphasis on Climatic Variability. More emphasis and work should be done to better understand and use the knowledge about the effect of shorter term climatic variability on the resource sector. Industry has to cope with existing and future conditions. Little use is made of available normals because they do not reveal the risk that climate poses to any particular resource sector. A better understanding of existing climatic variability and its effect on any given sector would aid planning. This would demonstrate greater utility of climate data and provide support for impact assessment efforts applied to future climatic change scenarios. Quite possibly, the strategies developed to cope with present climatic variability would aid in coping with a future climatic change.

## 2.4 WORKSHOP 4: CAN WE QUANTIFY THE LINKS BETWEEN CLIMATE AND OUR RESOURCES?

Facilitator: R. Lawford, Canadian Climate Centre
Recorder: E. Kerr, Alberta Environment

This working group was asked to assess the linkages between climate and the resource sector. The workshop group included a university professor, government scientists and managers, a farmer, an operational flood forecaster, and resource planners. Although the discussions were wide ranging, they centered on two factors influencing these linkages, namely our abilities to define present and future climatic states and, given this information, to determine the effects of these states on the natural resource base. It was the group's consensus that the greatest need lies in defining the present and future climatic states. In addition, there are also requirements to improve our understanding of the links between climatic variability and change and the resourse base. However, these needs vary according to the resource sector and the time scale.

As a result of its deliberations, the group identified the following priority issues:

1. **Is there predictability in the atmosphere at time scales of one month and longer?** It was felt that predictions of climate in the one week to one season time frame were more important to planners and resource managers than scenarios 30 to 50 years in the future. However, if it is proven that there is no possibility of predicting climate on a monthly to seasonal time scale, as the models suggest, then efforts should be focussed on the one- to two-year time scale where influences such as the El Nino have been shown to be significant.
2. **Is it possible to more effectively parameterize the small scale atmospheric processes, such as the hydrologic cycle, and to produce future climate scenarios with more reliable estimates of precipitation?** In reviewing the model outputs, it was noted that one of the most unreliable outputs are the precipitation scenarios. This output parameter, along with temperature, is the most critical in determining the response of the resource base to climatic change. Part of this uncertainty arises from the difficulty of reliably parameterizing precipitation processes.
3. **How can we more effectively define and communicate the uncertainty associated with assessments of the impacts of climatic change on resources?** It was felt that too much credibility was placed by users on the results of impact studies. Some of the uncertainties arise from the quality of the climate scenarios, the nature of the transient response of the atmosphere to the warming, and difficulties in scale matching?
4. Although a great deal of progress has been made in a number of resource sectors, **is there an adequate understanding by resource**

managers of the linkages between available climatic variability and future climate scenarios and changes in the resource base? Workshop participants felt the knowledge of the links between climate and the resource base varied with resource sector and the time scale. For example, in agriculture the linkages on the longer time scales are quite well established, however, they are less well known on the shorter time scales. On the other hand, more research is needed to understand how the forests and forestry operations would be modified over longer time scales to respond to changes in climate scales.

As a result of the further deliberation on these issues, the working group recommended that the following steps be taken:

1. A review should be carried out by federal and provincial agencies to determine the types of impact assessments within each resource sector which are possible given the present level of climate data and model outputs. In areas where it is not feasible to undertake impact assessments, it would be desirable to carry out additional research on the linkages between climate and the resource base.
2. Atmospheric Environment Service, in consultation with users, should undertake an assessment of the degree to which each GCMs 1 x $CO_2$ climate scenario approximates Canada's present climate. Use of the models which perform well should be encouraged in order to facilitate the intercomparison of impact assessment methodologies.
3. Atmospheric Environment Service and Canadian universities should become initimately involved in international programs directed at studying the limits to the predictability of the atmosphere.
4. Further studies should be carried out to determine the way and the rate of change for the response of climate and the resource base to increasing atmospheric $CO_2$ levels.

## 2.5 WORKSHOP 5: IS THERE SUFFICIENT COMMUNICATION REGARDING CLIMATE AND ITS IMPACTS?

Facilitator: T. O'Brien, Agriculture Canada
Recorder: K. Jones, Atmospheric Environment Service

The objective of this workshop was to address the current communication mechanisms which exist to promote dialogue between all parties interested in climate and its impacts. These mechanisms included topics such as media, publications, and workshops. Participants were encouraged to comment on their communications concerns, issues, and needs interprovincially; intersectorally (between forestry, hydrology, agriculture, tourism, etc.); and interfunctionally as users, researchers, policy makers, etc.

All participants were given an opportunity to identify their concerns. In excess of 20 concerns were identified from a wide range of discussions and priorized by the participants. The issues considered most important by the participants were:

1. The reality of our weather and climate is that it is variable. In an effort to make the information easier to understand, there is a tendency to simplify, to average, and to refer to normals. Is variability within our weather and climate adequately communicated or has it been oversimplified in an effort to be more easily perceived? Is the perception of normal conditions leading to an expectation of weather and climate conditions that are more stable than should be anticipated? Users need to know that the range of variability and normals are not sufficient descriptions.
2. Under changing climate conditions, it may be expected that periods which are near to average (albeit a changing average) will not create as much impact as the periods of more extreme events. Sectors, such as agriculture, adapt continually to conditions that we learn may be expected, but we are vulnerable to the extremes that have lesser frequencies. These extremes often have a very significant impact on our normal operations.

What is the skill level for identifying variability under conditions of climatic change? Is there sufficient skill in defining the extremes and frequencies of events to justify communicating these results and determining the social and economic consequences? What level of skill is necessary?

3. It is often apparent in climate related studies that specialists carry out analyses without adequate appreciation for the data which is used. Likewise, it is apparent that the providers of data often have little appreciation for how the data will be used. Relative to the topic of this Symposium, what is the assessment process for models of the GCM type? Do climate impact and socio-economic modellers have the information required to choose appropriate models, sets of models, and data for analysis? How can the models be sufficiently tested? How may it be assured that impact analysis is carried out with proper data? Should there be a critical independent review of general circulation models before further climate impact analyses are carried out? Are the impact models capable of analyzing conditions under changing climate? What accuracy and what method of verification should be expected from these model outputs?

The list of issues were reviewed by workshop facilitators, reworded, and distributed among the workshops to formulate recommendations. This exercise clarified the main issues and reduced the number of issues to a manageable number. Five recommendations were formulated:

1. An interdisciplinary approach must be used in climate studies to ensure direct, comprehensive communication between users and providers.
2. Users must communicate their needs, and providers must be informed and provide advice on the application of data to ensure that the appropriate information is used.
3. Impact analysis specialists using the output from general circulation models (GCMs) should not attempt to determine, in isolation, the appropriate GCMs for their purpose. This is the essence of Recommendations 1 and 2.

4. Results of any model output must be communicated with inherent errors and assumptions identified, qualified, and quantified by the modellers.
5. A more comprehensive understanding of climate relating to applications of weather and climate in an interdisciplinary context should be promoted through education programs at all learning levels . This could be a role for educators and Climate Advisory Committees to assist in.

## 2.6 WORKSHOP 6: WHAT ARE THE SOCIO-ECONOMIC IMPACTS OF CLIMATIC VARIABILITY AND CHANGE?

Facilitator: G. Schaefer, Atmospheric Environment Service
Recorder: J. Tokarchuk, Manitoba Agriculture

The group initially considered the content of the technical presentations insofar as they dealt with socio-economic impacts. It was agreed that impacts significantly affecting society had been elucidated, including those directly affecting the physical resource base and those involving a broad range of human activities.

Members of the group then brought forward issues based upon their individual perspectives. These were then consolidated and ranked. The list below indicates the identified issues starting with that considered most important. Issues numbered 6, 7, and 8 and those numbered 10 and 11 were given equal rank.

1. **Is there an adequate methodology or framework to carry out socio-economic impact studies?** Such a framework should be capable of comparing scenarios with and without climatic change. The scope of assessment, ranging from global through national and regional scales to the local scale, is an important consideration.
2. **Is solid information on the first order effects of climatic change and variability available?** This questions relates to our ability to model the relationship between climate and our physical resources.

3. **Do we have adequate information on the projected rates of change of climate and on the resultant rates of response in our resource sectors?** Rates of change are crucial in determining how society will be affected and in planning how it can best respond.
4. **Can we go further than developing scenarios at this time?** This question has as its focus uncertainty in our knowledge of climatic change. At what point is it appropriate to present findings as projections rather than considerations of a range of possible but uncertain futures?
5. **Should the emphasis in socio-economic assessments be on climatic change or variability?** This issue took note of a number of presentations which pointed to the need to address the impacts of variability to meet "bread and butter" information requirements of resource planners and managers.
6. **Are processes to make associated social and political decisions being adequately considered?** The ability to take appropriate action based on assessments carried out implies the presence or development of such processes.
7. **Is the human dimension of socio-economic impact being taken account of?** This question relates to the flexibility, vulnerability, and adaptability of society.
8. **Are the public and the policy makers being properly informed and educated about the socio-economic impacts of climatic variability and change?**
9. Will policies developed to deal with the socio-economic impacts of climatic variability and change retain sufficient flexibility to deal with "surprises" that may arise?
10. Can we identify and place in order of priority the key resource sectors which should receive more immediate attention for socio-economic impact assessments?
11. How certain are we of the fact, direction and rate of climatic change and of socio-economic impact assessments made on that basis? **What are the impacts of being wrong? This issue is related to that in No. 4 above.**

12. **Are sufficient professionally and technically trained human resources available to carry out the studies and assessments required?** Interdisciplinary teams will have to be assembled to successfully complete the work.
13. **Are the possibilities for technological response being addressed?** Under what circumstances will such a response be worthwhile in dealing with either the positive or negative consequences of climatic variability and/or change?

The group developed three recommendations based upon the issues identified earlier and subsequent discussion in plenary session. They are listed below, without regard to priority, as presented for consideration by the final plenary session.

1. It is recommended that interdisciplinary working groups be formed to facilitate information exchange in the area of climate modelling and impact assessment. A primary operational function of the working groups would be to develop appropriate methodological frameworks to utilize socio-economic impact assessment techniques with available climate data and modelled rates of change in both the climate and the resource base.
2. It is recommended that emphasis be placed on identifying and specifying rates of resource response to climatic change. Such information is significant to socio-economic impact assessment.
3. It is recommended that socio-economic impact assessments initially (in the next phase) concentrate on developing an improved understanding of the effects of climatic variability. Such an emphasis would meet the current needs of many operational managers and planners. Development of knowledge and coping mechanisms to deal with climatic variability would go a long way towards preparing society to deal with longer term climatic change.

## 3. SUMMARY OF RECOMMENDATIONS PRIORIZED BY THE PLENARY SESSION

The issues and recommendations generated from each workshop were presented and reviewed at a plenary session. Related issues and recommendations were grouped together and the resulting 21 recommendations were priorized to provide clear direction for future initiatives including research and monitoring. The recommendations in order of priority are:

1. a. Prepare a state-of-the-art report on application models to inventory and evaluate the capabilities and limitations by resource sector and scale (temporal and spatial);
   b. Inventory all available climate data; and
   c. Compare 1a and 1b.
2. Given the uncertainty surrounding climatic change, socio-economic impact assessments should concentrate initially on the development and understanding of the effects of climatic variability.
3. Atmospheric Environment Service, in consultation with users, should undertake an assessment of each GCMs (1 x $CO_2$) outputs to determine which can best approximate Canada's present climate and to recommend a "standard" for impact studies.
4. An effort should be made to at least maintain and preferably increase (better) monitoring of climate related parameters (e.g., vegetation cover) to detect climate trends. Establish a more comprehensive "Western Canadian" climate station network which reflects the interdisciplinary requirements of the various user groups.
5. Direct efforts into mesoscale research to improve parameterization in General Circulation Models (GCMs), to improve mesoscale models for use in GCMs, to develop more highly detailed models to test highly parameterized models within GCMs.
6. An interdisciplinary approach must be defined in climate studies to ensure direct comprehensive communication between users and providers.

7. Provincial/Territorial Climate Advisory Committees should develop plans to promote the communication of current climate issues and their implications for society; the plan should include a mechanism to determine the needs of policy makers and resource managers.
8. Interdisciplinary working groups should be formed to facilitate information exchange in the area of climate modelling and impact assessment. A primary operational function of the working groups would be to develop appropriate methodological frameworks that utilize socio-economic impact assessment techniques with available climate data and modelled rates of change in both the resource base and the climate.
9. Provincial/Territorial Climate Advisory Committees should identify priority economic sectors and develop research proposals to address their most immediate needs with particular respect to the possible effects of climatic change and variability.
10. a. Identify user needs and develop a marketing strategy to promote availability and use of climate data.
    b. Educate climate users about topic and providers about applications.
11. Given the present status of climate monitoring and data availability and model outputs, a review of the types of assessments that are feasible within each resource sector should be carried out.
12. Promote the awareness of climate through education programs at all levels of learning, which will relate the application of weather/climate in an interdisciplinary and social context.
13. Further studies should be done by Atmospheric Environment Service and resource agencies on the way (plus rate) in which climate and the resource base will change as a result of increasing atmospheric $CO_2$.
14. Federal and provincial governments should expand monitoring programs and continue to promote control strategies.

15. It is recommended that emphasis be placed on identifying and specifying rates of resource response to climatic change. Such information is significant to socio-economic impact assessments.
16. Results of any model output including the inherent errors and assumptions identified and qualified must be communicated to each level of user.
17. Expand air-sea interaction research and link (oceans) to climate models.
18. Improve regional, national, and international cooperation for exchange of information (e.g., data to help develop and test climate and impact models).
19. Users must communicate and providers must be aware of intended applications to ensure that the appropriate information is provided.
20. Atmospheric Environment Service should undertake a study of the limits to the predictability of the "real" atmosphere (i.e., not a model's atmosphere).
21. Impact analysis specialists should not be responsible for choosing models and must utilize recommendations.

These 21 recommendations were further reviewed by the Alberta Climate Advisory Committee and condensed into the following seven summary recommendations. The original recommendations supporting the merged set are listed in parenthesis. The summary recommendations were then distributed to the other western Climate Advisory Committees and the Canadian Climate Program Planning Board for consideration.

1. State of the Art. Given the variety of assessment tools available definitive state-of-the-art reports are required for both global circulation models and application models to recommend which are the most appropriate for use in western Canada (Recommendations 1a, 1c, 3, 16, and 21).
2. Variability. Given the uncertainty surrounding climatic change, socio-economic impact assessment should initially focus on climatic variability and its effects (Recommendation 2).

3. Monitoring. Environmental monitoring programs operated by government must be maintained or enhanced to ensure that trends in both climate and resource impact can be identified and intercompared (Recommendations 1b, 4, and 14).
4. External Communication. A major initiative is required to communicate with policy makers, educators and the general public on regional climatic variability and change issues (Recommendations 7, 10a, 10b, and 12).
5. Internal Communication. Efforts must continue to ensure that interdisciplinary and interagency communication on climatic variability and change issues are enhanced (Recommendations 6, 8, 18, and 19).
6. Model Improvement. Efforts must continue to be directed into improving the quality and resolution of global circulation models (Recommendations 5, 17, and 20).
7. Priority Sectors. Given the climatic variability and change will have wide ranging impact in western Canada, the priority economic sectors must be identified, their rates of response to climatic trends must be documented, and the development of mitigative strategies is to be encouraged (Recommendations 9, 11, 13, 15, and 17).

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